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MASTER'S THESIS

Innovative in situ remediation techniques in the Netherlands

Opportunities and barriers to application in Sweden

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Preface

This report is the result of graduation research for the Master program in Environmental Engineering at Luleå University of Technology. The project was conducted on commission by Tyréns, Division of Environmental geotechnology and land pollution. The research was carried out during one year in the Netherlands as an exchange between Tyréns and a Dutch engineering consultant firm Witteveen+Bos, which are both partners of the knowledge exchange network SEEN (Strategic European Expertise Network).

The working process during the research has not been completely straightforward. The research started with the purpose to identify new in situ techniques in the Netherlands that could be applied in Sweden. However, the results showed soon that most of the innovative techniques used in the Netherlands are already known in Sweden, but not applied in practice. The second part of the report was therefore aiming at identifying differences between Sweden and the Netherlands that could explain why innovative in situ techniques are more often applied in the Netherlands. I hope that the reader finds the subject of this report interesting and that the report gives insight in the Dutch soil remediation and ideas on how to stimulate the use of innovative remediation techniques in Sweden.

There are several persons who have been involved in this research and to who I would like to give my thanks. First of all I would like to thank everyone that have taken part of the questionnaire, interviews, and provided with information to the case studies or other interesting information during the research.

Special thanks to all the colleagues at Witteveen+Bos in Maastricht for all the fun and support during the time in the office. Together with you there is always a time for a good laugh! I also want to thank my boyfriend, Richard Edelhausen, for having the enormous patience and supporting me to finish this project.

Finally I would like to thank my supervisors at Witteveen+Bos, Rina Clemens and Pieter Hoefsloot, and also Erwin van de Pol at Witteveen+Bos for providing me valuable information on soil remediation in the Netherlands; my supervisor at Tyréns, Berith Juvonen, my examiner at Luleå University of Technology, Christian Maurice and my opponent Katarina Elvfersson for the valuable ideas and comments helping me to improve the report.

Maastricht, the Netherlands in October 2007

Maja Örberg

Summary

After more than ten years of intensified activity within the field of remediation of contaminated sites, the most commonly applied remedial solution in Sweden is excavation. Today there are few alternative solutions available in Sweden, which results in high price levels and few opportunities to select techniques with respect to least negative environmental impact. Whereas alternative remediation techniques are developed in other countries, the application is limited in Sweden.

The Netherlands are considered to be one of the leading countries within the field of soil and groundwater remediation. The aim of the thesis is to identify new in situ remediation techniques in the Netherlands that could be suitable to apply in Sweden. The aim is also to identify the most important opportunities and barriers to new in situ techniques in Sweden. The report focuses on techniques suitable for remediation of sites contaminated with petroleum- and chlorinated hydrocarbons.

The research is based on literature studies and interviews with key persons. A case study of five Swedish and six Dutch in situ remediation projects was carried out. Finally, an investigation on the experiences of persons active within remediation branch in Sweden was carried out with means of a questionnaire.

In general there is in the Netherlands a wider range of different remediation techniques available which can be applied in practice. The in situ techniques identified in this report, with no previous known application in Sweden, are; co-solvent or surfactant flushing, LINER, six-phase heating, electro bio reclamation, electro kinetic bio screens, in situ chemical oxidation with C-sparge and perozone.

None of the techniques can be excluded to be suitable to apply in Sweden with respect to environmental criteria such as soil structure, since the environment is unique at each specific site. The variation of the site-specific environment is great between different sites in Sweden. All the techniques have, at appropriate environmental conditions, the potential to reduce the pollution level to correspond acceptable risk levels in Sweden.

Many of the new techniques that are regularly used in the Netherlands are known in Sweden, but not applied in practice. In this report differences between Sweden and the Netherlands are identified that can may explain why Sweden apply less innovative in situ techniques.

Factors that do not differ between Sweden and the Netherlands are apart from type of contamination, the applied remediation goals, costs and time aspects. Factors that might differ between Sweden and the Netherlands are the soil structure, climate and the costs of in situ techniques compared to other techniques. Factors that do differ between Sweden and the Netherlands are the involvement of contractors in making the remediation plan, the overall strategy of a remediation, the remediation policy, the experience and available guidance of performing different in situ techniques. Demonstrations of new in situ techniques in Swedish environments would the best and most important opportunity to increase the experience and stimulate implementation of new in situ techniques in practice.

Sammanfattning

Efter mer än tio år av ökad aktivitet inom området efterbehandling av förorenade områden är urgrävning och transport till behandlingsanläggning eller deponi den vanligaste åtgärdslösningen vid sanering av förorenade områden i Sverige. Idag finns få alternativa åtgärdslösningar tillgängliga i Sverige, vilket resulterar i höga prisnivåer och få möjligheter att välja teknik med avseende på minsta möjliga miljöpåverkan. Medan alternativa tekniker etablerar sig i andra länder, har dessa fått en begränsad tillämpning i Sverige.

Nederländerna anses vara ett av de ledande länderna inom efterbehandlingsområdet. Syftet med examensarbetet är att identifiera nya in situ tekniker i Nederländerna som skulle kunna tillämpas i Sverige. Syftet är även att identifiera de viktigaste barriärerna och möjligheterna för tillämpning av nya in situ tekniker i Sverige. Arbetet fokuserar på tekniker lämpliga för efterbehandling av områden förorenade med petroleum- och klorerade kolväten.

Arbetet har genomförts genom litteraturstudie samt intervjuer med olika nyckelpersoner. En fallstudie av fem svenska samt sex nederländska in situ saneringsprojekt har genomförts. Slutligen har en enkätundersökning genomförts på personer verksamma inom den svenska efterbehandlings-branschen.

Generellt finns det i Nederländerna ett bredare utbud av olika tillgängliga efterbehandlingstekniker som kan tillämpas i praktiken. De nya in situ tekniker som tillämpas i Nederländerna och som identifierats i detta arbete är; lösningsmedelsextraktion, LINER, six-phase heating, electro bio reclamation, electrokinetical bio screens, in situ kemisk oxidation med C-sparge och perozone.

Det finns flera olika faktorer som avgör om en in situ teknik är tillämpbar på en specifik plats. Av de tekniker som identifierats i denna rapport kan ingen uteslutas för tillämpning i Sverige med avseende på geologiska eller klimat förutsättningar. De platsspecifika förhållandena varierar stort mellan olika platser i Sverige och avgör om metoderna kan tillämpas eller inte. Vid lämpliga miljöförhållanden har samtliga tekniker potential att reducera föroreningshalterna till motsvarande acceptabla risknivåer i Sverige.

Många av de innovativa sanerings tekniker som tillämpas i Nederländerna är redan kända i Sverige, men tillämpas ej i praktiken. I rapporten identifieras skillnader mellan Sverige och Nederländerna som skulle kunna föklara varför Sverige mer sällan tillämpar innovativa in situ tekniker.

Faktorer som ej skiljer mellan Sverige och Nederländerna är, förutom föroreningstyp, de mätbara sanerings mål som tillämpas, samt kostnads- och tidsaspekter. Faktorer som kan skilja mellan Sverige och Nederländerna är de geologiska- och klimatförutsättningarna samt kostnad av in situ tekniker i förhållande till andra tekniker. De faktorer som skiljer mellan Sverige och Nederländerna är entreprenörens deltagande i utformningen av saneringsplanen, tillämpade saneringsstrategier, saneringspolicy, samt erfarenheten och tillgång till vägeldningsmaterial med avseende på tillämpning av nya in situ tekniker. Den bästa och viktigaste möjligheten att stimulera användandet av nya in situ tekniker torde vara att genomföra demonstrationsprojekt i svenska miljöer.

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1 Introduction

1.1 Background

Remediation of soil and groundwater is a rather new activity in Sweden, which has been intensified during the last ten years. The increased activity of soil- and groundwater remediation is mainly a response to the environmental quality objective "a non-toxic environment" which is one of the 16 environmental quality objectives the Swedish Parliament adopted in 1999 and 2005. Today there are approximately 83 000 potentially contaminated sites in Sweden[1]. The objective is to solve the problem of these sites before year 2050[2]. Due to historical activity many sites throughout Sweden are polluted with contaminants such as petroleum hydrocarbons and chlorinated solvents. A main part of these sites is located in more densely populated areas posing a risk to human health and the environment and must therefore be remediated.

Remediation itself is an activity with negative environmental impact in terms of transports and use of native materials. This may lead to conflict between the different national environmental quality objectives such as "a non-toxic environment", "reduced climate impact" and "a good built environment". Several different remediation methods are available today and each can be evaluated on different aspects, such as transport and use of energy Excavation and transport to following off site treatment or land filling is a method having bad impact on this aspect. However, excavation and transport is still the most common solution to manage contaminated sites in Sweden[3]. Whereas alternative techniques are establishing in other countries these have been limited applied in Sweden. As a result there are today few alternative solutions for remediation of soil- and groundwater pollution, resulting in high price levels and few opportunities to select techniques with respect to least negative environmental impact[4]. To increase our knowledge in soil remediation it has been suggested to make use of international experiences of remediation techniques and methods[5].

In the Netherlands remediation of contaminated sites started in the early 1980s. In comparison to Sweden, the Netherlands is considered to have long experience of using different remediation techniques[6]. Technology as well as legislation have been developed during the past 25 years and today the Netherlands are reputed to be one of the leading countries in the field of soil- and groundwater remediation. The Netherlands advance is attributed to the ability of e.g. performing in-situ remediation techniques that are not performed in the rest of Europe.

1.2 Goals

The aim of the project was to identify the differences between Sweden and the Netherlands with regard to applied in situ remediation techniques, identifying whether there are new in situ remediation techniques that can be applied in Sweden.

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[1] Swedish EPA (2007-06-05)
[2] Miljömålsportalen (2007)
[4] Helldén. J., *et.al* (2006)
[4] *Ibid.*
[5] Swedish EPA (2002)
[6] Swedish EPA (2003)

The aim was also to investigate potential reasons that could explain the identified differences between Sweden and the Netherlands. Both technical and social factors were included in the study. The investigation was also aiming to identifying the main opportunities and barriers to new in situ techniques in Sweden. Finally, suggestions on how to stimulate the development and use of new in situ technologies in Sweden would be given.

1.3 Limitations

Remediation of oil polluted sites started for about 15 years ago, but there are still many sites to remediate, meaning that large amounts of soil and groundwater have to be decontaminated. Chlorinated solvents have for various purposes been used to a great extent in Swedish industry resulting in pollution of soil and groundwater at many sites. Until recently this kind of pollution had received very little attention in Sweden, but as chlorinated solvents today pose a threat to many groundwater assets this situation has changed. The awareness of these sites is increasing in Sweden and hence leading to remediation of a large number of sites in the near future[7]. Considering previous discussion, this report is limited to survey techniques for remediation of soil and groundwater contaminated with petroleum hydrocarbons or chlorinated solvents.

The report is focused on innovative in situ remediation technologies that are commercially available and not only exist at a development stage.

The aim of this report was not to provide any detailed analysis of the applicability of the identified new in situ techniques in Sweden. The aims of the report were instead to make identification and provide an overview of the new techniques, as an introduction to further studies. Further the report is limited to give an overview of the main differences between Sweden and the Netherlands, opportunities and barriers identified by the author, and does therefore not necessarily cover all.

1.4 Report structure

The method of the investigation is described in chapter 2: *Method*. In situ remediation techniques that are applied in Sweden and the Netherlands are investigated, and new techniques that can be applied in Sweden, are identified in chapter 3: *Identification of new in situ techniques*. An analysis of the applicability of the new techniques in Sweden is performed with respect to the most important aspects for the success of the techniques in chapter 4: *Analysis of applicability in Sweden*. By a comparison between Sweden and the Netherlands some of the most important barriers and opportunities in general to new in situ techniques in Sweden are identified in chapter 5: *Barriers and opportunities to new in situ techniques in Sweden*. Finally the results are discussed more general and lead to suggestions of improvements for new in situ techniques in Sweden in chapter 6: *Discussion.* Conclusions and suggestions to further research are presented in chapter 7: *Conclusive remarks*.

[7] Englöv. P., *et.al* (2007)

2 Method

2.1 Literature study and interviews

The thesis was initiated with a literature study on the actual topic in order to obtain an overview of the remediation situation in Sweden and the Netherlands and collect sufficient background information to define the problem area. Literature was also collected in order to study the factors impacting on the decision-making process of remediation techniques. The results were used to create a questionnaire (see 2.2) and to create relevant questions in order to study Swedish and Dutch remediation projects, see 2.3.

The literature study continued in parallel to the whole working process in order to investigate differences between Sweden and the Netherlands regarding applied in situ remediation techniques and the opportunities and barriers of applying new in situ remediation techniques in Sweden. Various literatures within the field of soil- and groundwater remediation such as current legal provisions and environmental guidelines have been surveyed. The literature was mainly found on the Swedish environmental protection agency, the Swedish geotechnical institute (SGI), the Netherlands ministry of housing, spatial planning, and the environment (VROM international), the Netherlands centre for soil, quality management and knowledge transfer (SKB), CLARINET, and US environmental protection agency (USEPA). Articles on various issues were collected on Google Scholar and databases available at the homepage of the library of Luleå technical university.

In case of insufficient or unclear information in the literature, interviews with persons active within the field of soil remediation (advisors, authorities, contractors) in Sweden and the Netherlands have been carried out.

2.2 Questionnaire

Based on the findings in the literature study, a questionnaire was compiled in order to survey the most significant barriers and opportunities to apply innovative remediation techniques experienced by the Swedish remediation branch. The questionnaire was used in order to investigate the perceived barriers to implementation of innovative remediation techniques in Sweden. The target group of the questionnaire was different persons active within the field of soil and groundwater in Sweden. A first round of the questionnaire was handed out in November 2006 at the annual meeting of the Northern Sweden soil remediation centre (MCN). A second round was later handed out in December 2006 by e-mail, addressed with help of contacts within the national clean soil network, Nätverket Renare Mark (NRM). Due to insufficient material from a few groups of representatives (authorities), information was also obtained by supplementary interviews based on the questionnaire.

2.3 Case studies and interviews

Case studies of Swedish and Dutch remediation projects are compared in order to describe what techniques are applied, how the selection was made and to identify the main criteria influencing the selection of remediation method. 6 Swedish and 6 Dutch remediation projects are included in the study. Only cases where the decision making process is completed and the remediation work has begun or have been completed are included. The number of cases chosen for the study is a small number compared to the total number of remediated sites in Sweden and the Netherlands. Swedish cases have been selected from an overview of Swedish remediation projects carried out between 1994 and 2005, published by the Swedish Environmental Protection Agency[8]. Dutch cases have been selected from an engineering consulting firm of average size with activity within the field of soil and groundwater remediation. Cases were selected from ongoing or recently performed projects, and would be examples of state of the art technology available in the Netherlands at the moment.

Various paper key documents such as remediation plans and remediation reports from the different cases have been used as documentation source. Supplementary information, such as information concerning the selection of remediation technique has been obtained through personal or e-mail contact with responsible persons in each case such as technical advisors, authorities and problem holders.

[8] Helldén. J., *et.al* (2006)

3 Identification of innovative in situ techniques

The objective of this report was to identify new in situ remediation techniques in the Netherlands that could be suitable to apply in Sweden. A first step was to identify what techniques were applied in the two different countries. An overview of the applied in situ techniques and their status in Sweden and the Netherlands is available in appendix 1. In this chapter differences between Sweden and the Netherlands regarding applied in situ remediation techniques are identified. Finally an overview of techniques that are new to Sweden is presented. The purpose is not to give a detailed description of the new techniques. Instead a brief description of the techniques and an overview are available in appendix 2 and 3.

3.1 In situ techniques applied in Sweden

Approximately 1200-1500 remedial operations where reported in Sweden during the years 1994-2005. 1/6 of these projects where investigated in a survey carried out by Helldén. J. *et al.* during 2006. In situ remediation methods where applied in 10% of the cases, as a sole solution or in combination with ex situ methods. Additionally 300 remediation projects carried out by the Swedish petroleum institute environmental fund (SPIMFAB) since 1997 where included in the survey. In 6% of the projects in situ methods alone or a combination including in situ methods where applied[9]. Information from the survey serves as the starting point in this investigation.

Since 1994 the most commonly applied in situ remediation techniques in Sweden have been:

- groundwater extraction
- soil venting or soil vapor extraction
- biological degradation and sparging methods.

Other in situ techniques have been applied in Sweden by pilot-, field- or full-scale demonstrations, such as steam injection, monitored natural attenuation and in situ chemical oxidation with Fenton's reagent. Chemical oxidation with sodium percarbonate and granule peroxide has been successfully applied in a full-scale remediation project on an operating petrol station. See case study "Petrol station Bottnaryd".

Helldén *et al.* show a decreasing trend between 1999 and 2004, regarding the use of in situ solutions in projects financed by SPIMFAB, whereas the total amount of projects have increased[10]. Figure 1 shows the applied strategy in projects financed by SPIMFAB.

[9] Helldén. J., *et.al* (2006)
[10] *Ibid.*

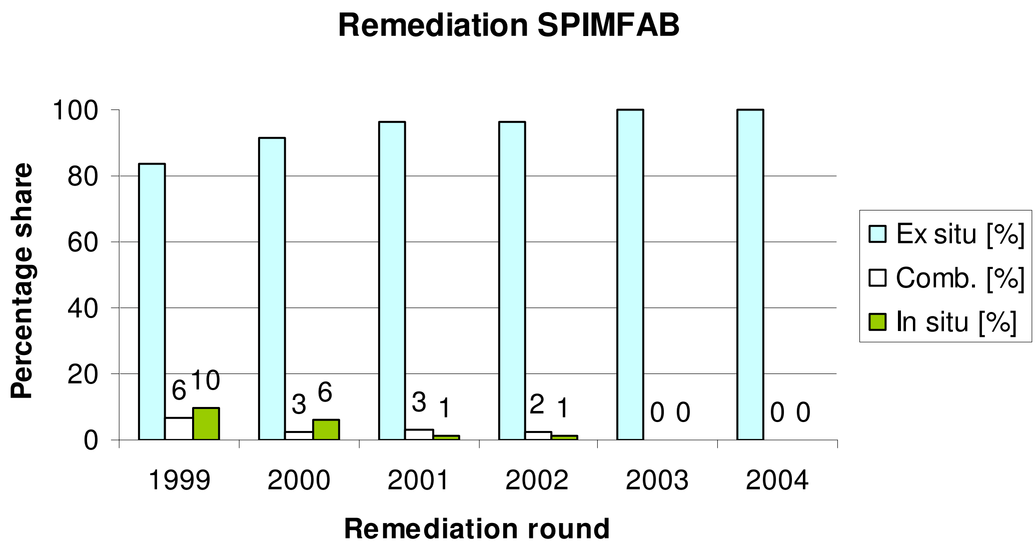

Figure 1. Applied remediation strategy in remediation projects funded by SPIMFAB. Remediation rounds 1-6 carried out 1999/2000-2004[1].

During the first active years of SPIMFAB, there was a shortage of suitable ex situ treatment plants for treatment of the contaminated soils, especially in Northern Sweden. Therefore in situ remediation was a good option, since it was not economically feasible to transport excavated soils to treatment plants. In situ technology was rather new and its limitations not well known and in many in situ remediation projects the technique did not perform as expected. Today there are more ex situ treatment plants available and due to earlier bad experiences, in situ techniques are today used in a limited number of the remediation operations. Further, remediation projects financed by SPIMFAB often comprise rather small volumes (see table 6. p. 32.) of contaminated soil and groundwater and in situ technology is therefore not always a cost efficient solution[11].

A summary of applied techniques in the Swedish and Dutch case studies is shown in table 1. The most commonly applied in situ techniques in the Swedish case studies were soil vapour extraction and pump -& treat. The number of projects with in situ techniques applied in Sweden is limited, especially regarding remediation of chlorinated hydrocarbons. Important to notice is that most of the Swedish cases were carried out in the beginning of 2000, when soil vapor extraction, bioventing and sparging methods still were considered as innovative remediation techniques. Steam injection and in situ chemical oxidation with peroxide were applied in Boden 2000-2001, though with less successful results. However, these techniques are today still considered as innovative in Sweden[12]. Steam injection has so far only been applied in a few remediation projects in Sweden. Chemical oxidation with peroxide has not been applied in any known remediation projects since then.

[11] Helldén. J., *et.al* (2006)
[12] *Ibid.*

Table 1. Overview of remediation techniques applied in the Swedish and Dutch case studies.

Site	Year	Contaminants	Applied techniques	Goal achieved	Completing technique
Ludvika	2001-2003	PHC[13]	Steam injection, SVE, pump&treat	No	Excavation
Lerum	1999-2002	CHC[14]	SVE, pump&treat	No	Further investigation of hydrogeological situation and constructional measures.
Götene	2003	PHC	SVE, bioventing, pump&treat	Yes	Not needed
Haninge	2001-2005	PHC	SVE, biosparging, pump&treat	No	Biostimulation, excavation
Bottnaryd	2005	PHC	Chemical oxidation with KEMOX	Yes	Not needed
Boden	2000-2001	PHC	SVE, Steam injection, ISCO Peroxide	No	Excavation
Utrecht	2007- On going	CHC	ISCO C-Sparge, co-solvent flushing , pump&treat	Not completed	-
Markelo	2002-on going	PHC	Excavation, biosparging, SVE, pump&treat	Yes	Groundwater extraction, monitoring
Ermelo	1999-on going	PHC	ISCO Fenton's Reagent, SVE, triple phase extraction	No	Groundwater extraction, monitoring
Oosterhout	2004-on going	PHC	ISCO Peroxide, SVE, air sparging	No	Multiphase extraction
Hilversum	2007-on going	PHC	Excavation, ISCO Fenton's reagent, pump&treat	Not completed	-
Gent	2006-on going	PHC	ISCO Fenton's reagent, SVE	Not completed	-

[13] PHC = petroleum hydrocarbons
[14] CHC = chlorinated hydrocarbons

3.2 In situ techniques applied in the Netherlands

Information about commonly applied in situ remediation methods in the Netherlands has mainly been obtained from the website of the organisation SKB (Stichting kennisontwikkeling kennisoverdracht bodem). Within the Netherlands Eurodemo project, an overview has been created of the broad palette of in situ technologies that currently are being applied by contractors in the Netherlands. Based on the information found at the SKB website an overview of the in situ techniques that are applied in the Netherlands and the status of the techniques is presented in appendix 1.

Remediation of polluted soil and groundwater started in the Netherlands in the beginning of the 1980s. Unlike Sweden, there are no surveys available reporting the number of in-situ operations carried out in the Netherlands during these years. An exact comparison to Sweden of the number of in situ operations carried out is therefore difficult. However, during the time period 1980-2002, a total of approximately 9 300 cleanup operations were completed in the Netherlands. In total 1 447 site remediation operations where completed during the year of 2005[15], which is approximately the same amount of remedial operations that were reported to Swedish authorities between 1994 and 2005[16].

The development of the remediation policy in the Netherlands during the years has influenced the use of technique and methods. The first remediation of soil and groundwater in the Netherlands was the remediation of a residential area in Lekkerkerk outside Rotterdam in 1981. There is a visible correlation between what remediation techniques have been applied in the Netherlands since then, and the change into present soil remediation policy. Four phases of development and use of remediation technology can be recognised:

Beginning of the 1980s:
Contaminated soil was excavated and treated off site by physical or chemical methods. Contaminated groundwater was decontaminated in the means of pump and treat[17].

End of the 1980s and the beginning of 1990s:
Containment in the means of isolation, maintaining and control (IMC) methods was applied more often. IMC methods could be used in case of full removal of the contamination, but was not always considered cost efficient or technically possible. There was also an increase in the development and application of techniques based in situ biological treatment of groundwater[18].

End of 1990s and beginning of 2000:
The interest for more extensive and cost-effective remediation techniques increased, due to the change to a functional oriented remediation policy in 1997. In 2002 the most commonly applied in situ methods where pump and treat, electro-reclamation, soil vapor extraction and bioventing, sparging methods, steam injection and in situ biorestoration. Combinations of different methods were also increasing. Practical examples of different combinations are:

- soil vapor extraction and in situ bio restoration;
- sparging and soil vapor extraction and bio restoration;

[15] RIVM (2006)
[16] Helldén. J., *et.al* (2006)
[17] Chino. R (2006)
[18] Clarinet (2000)

- excavation of hotspots and in situ methods for the contamination plume

Innovative developments that became more commonly applied were; natural attenuation; phased anaerobic breakdown of chlorinated hydrocarbons; bioscreens; multiphase vacuum extraction (bioslurping); chemical or biological fixation; C-sparging technology[19].

Today (end of 2000):
In the Netherlands there is today a huge experience of:

- airsparging in combination with soil vapor extraction
- biosparging and bioventing
- in situ biological degradation (anaerobic and aerobic)

Extensive methods as biological degradation (aerobic and anaerobic) and natural attenuation are still applied in the Netherlands and combinations with excavation and pump- & treat are common. Because of experiences of lengthy remediation periods and pollutions left behind after completed remediation, the focus is now on short-term intensive remediation techniques[20]. In situ chemical oxidation with C-sparge or Fenton's reagent are examples of more intensive remediation techniques that have become more commonly applied in the Netherlands during the last few years. Other innovative techniques applied in the Netherlands today, but with less full scale experiences are[21]:

- Surfactant/co-solvent flushing
- Liner®
- Electro reclamation and electro bio reclamation (EBR)
- Electrokinetical bio screens (EBIS)
- Six-phase heating
- In situ chemical oxidation with Perozone
- Phase separation fluid pump (help technique)

More information on these techniques can be found in appendix 2.

The most commonly applied in situ techniques in the Dutch cases are chemical oxidation in combination with excavation or other in situ techniques. It should be noticed that these cases do not necessarily represent the situation in the Netherlands regarding applied remediation techniques. The Dutch cases are selected from projects with remedial solutions involving state-of-the art technique carried out by the Dutch engineering consultant firm Witteveen+Bos, who at the moment when this thesis was written predominantly involved in projects with in situ chemical oxidation[22]. The Dutch cases were carried out more recent (after 2002 and until today) than the Swedish cases. One explanation to why the Swedish cases selected for this study, was that the number of performed in situ operations in Sweden is very limited. In order to collect enough Swedish cases to this study, less recent projects also had to be selected.

[19] Clarinet (2002)
[20] Hoefsloot. P (2007)
[21] SKB-Eurodemo (2007)
[22] Hoefsloot. P (2007)

3.3 Innovative in situ techniques that are new to Sweden

By evaluating the results from chapter 3.1 and 3.2, in situ remediation techniques that are new to Sweden can be identified. There are techniques that are applied in the Netherlands, of which there is no known or limited experience in Sweden. These are presented in table 2. It should be noted that these techniques are considered as new to Sweden and not necessarily new in the Netherlands or other countries. Several techniques are not originally developed in the Netherlands, but in other countries such as United States of America. A description of the techniques is available in appendix 2.

Table 2. Overview of new in situ remediation techniques with no known or limited experience in Sweden

New in situ techniques with no application known in Sweden	**Techniques applied in demonstration or pilot projects**
• Co-solvent or surfactant flushing	• Reactive barrier with zero valent iron
• LINER®	• Anaerobic dechlorination (melass injection)
• Six-phase heating	• Monitored natural attenuation (MNA)
• Electro reclamation and electro bio reclamation (EBR)	• Steam enhanced extraction
• EBIS (electrokinetical bio screens)	• ISCO Fenton's reagent
• ISCO C-sparge	
• ISCO Perozone	
• Phase separation fluid pump (help technique)	

Finally a technique that has been applied in Sweden but not yet in the Netherlands is chemical oxidation by KEMOX. It should be noted that KEMOX is not a proper in situ technique since the soil partly has to be excavated in order to mix it with the oxidation granules.

4 Applicability of the new in situ techniques in Sweden

There are several factors deciding if a technique is suitable to apply on a specific site in order to reach the environmental goals drawn up in the most cost-efficient way. Lindmark and Larsson (1995) suggest several key factors that should be considered when selecting an effective remediation technique. In this chapter the applicability of the new techniques in Sweden will be analysed. The criteria that are the most important for the success of the techniques will be discussed. Focus will be on criteria that could differ between Sweden and the Netherlands. A brief description of the techniques and an overview of the suitable environmental conditions for application of the different techniques can be found in appendix 2 and 3. In order to understand the behaviour of petroleum- and chlorinated hydrocarbons in soil and groundwater and the different abatement mechanisms, a short description is given in appendix 4.

4.1 Description of the new techniques in the terms of abatement mechanism

In situ techniques are based on one or more mechanisms to abate pollution or a contaminated element in the ground. These mechanisms can be divided into extraction, destruction or stabilisation of pollution. Stabilisation is not an abatement mechanism since the pollution is still present in the ground, but further spreading of the pollution is limited. I extraction techniques pollution is abated by flushing via the water phase or volatilise via the gaseous phase. Convective transport mechanisms such as dispersion and advection are used. Destruction implies that the pollutant molecule is transformed, often in smaller molecules, and ultimately only CO_2 and H_2O remains. Destruction can be divided into biological or-, chemical destruction and incineration.

Based on the above named classification of abatement mechanisms the different in situ techniques identified in chapter 3, can be sorted. Table 3 shows an overview of the different in situ techniques classified with respect to abatement mechanism. The techniques depend often on one or more abatement mechanisms. Many techniques are also applied in combination with other more conventional techniques, which are based on extraction, such as groundwater pumping or soil vapor extraction.

Table 3. Overview of the different abatement mechanisms on which the in situ remediation techniques are based

Technique	**Abatement mechanism**		
	extraction	destruction	stabilisation
Co-solvent or surfactant flushing	++	-	-
LINER®	++	++	-
Six-phase heating	++	+	-
Electro bio reclamation (EBR)	+	++	-
Electrokinetical bio screens (EBIS)	-	++	-
ISCO C-sparge	-	++	-
ISCO Perozone	-	++	-

4.2 Environmental criteria

This chapter focuses on analysing criteria that may differ between Sweden the Netherlands. The criteria that may be the most different from the Netherlands are mainly environmental, such as geology, geochemistry and climate.

4.2.1 Geology

Geological conditions are very important for a successful remedial in situ operation. Most of the techniques presented in this report are based on extraction or destruction processes in the ground and the techniques are therefore often dependent on homogenous and permeable soils to achieve an effective remediation. The Swedish landscape has been formed and re-shaped by many different geological processes such as continental ice, land rising and rivers.

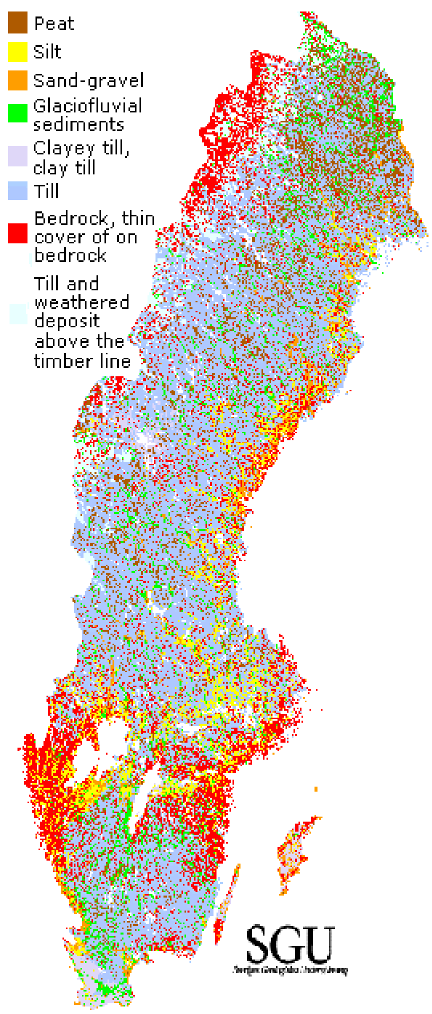

Figure 2. Soil parent material in Sweden (Markinfo, 2007).

As figure 2 shows, the most dominating soil in Sweden is till, which is a heterogeneous soil with low to moderate permeability. However the site-specific conditions vary greatly between different sites in Sweden and there are also places with more homogenous and permeable soils such as deposits of sand and gravel. Heterogeneous and low permeable or layered soils are in general a limitation to extraction or flushing through the soil, as the contaminants will migrate along the easiest way through the soil. Heterogeneous soil conditions leads to difficulties to achieve a satisfying spreading of injected substrate or gases. Another obstacle with heterogeneous soils is that canals appear easily when gas or groundwater is extracted while the soil volumes between these formations contain high concentrations of contamination and is difficult to reach with the techniques.

One example from Sweden where the in situ remediation was not successful due to low soil permeability is the remediation in Boden (case study 5). In situ ventilation in combination with steam injection, pump and treat and in situ chemical oxidation were applied. In situ ventilation tests on the neighbouring site showed good results, but the full-scale remediation failed. The technical advisor in this case believe that the ventilation probably only affected a limited volume of the ground. Also chemical oxidation was pre-tested in lab scale, showing promising results. In the field, this technique only had a minor remediation effect. An important aspect to consider is that soil venting with steam injection and in situ chemical oxidation were new remediation techniques in Sweden at that time (2000), and the experience was limited.

This may have had influenced the results of the remediation. On basis of the knowledge about the soil structure in the upper 10 meters, an indicative in situ map of the Netherlands has been drawn, where in situ techniques are more or less suitable to apply (Tauw, 2006). In figure 3 a map is depicted, dividing the Netherlands by suitable geological conditions with respect to in situ remediation. In the Netherlands suitable geological conditions for in situ techniques can be found in three large main areas in the south, central and the central-east of Holland. All Dutch sites in the case studies in this report are located in these areas. In general, the upper 10 meters of the ground consist of sand, which means good possibilities for in situ processes. Whereas in situ techniques are viable thanks to suitable geological conditions in these areas, other areas in the Netherlands have less suitable geological conditions. This is the case in the South of the province of Limburg, where the terrain is more hilly and the ground consists of fine compacted wind deposits (loess) over lime stone rock. In this area in situ techniques are not often applied[23]. At the moment, one project is planned where thermal heating will be applied to remediate petroleum-contaminated limestone[24].

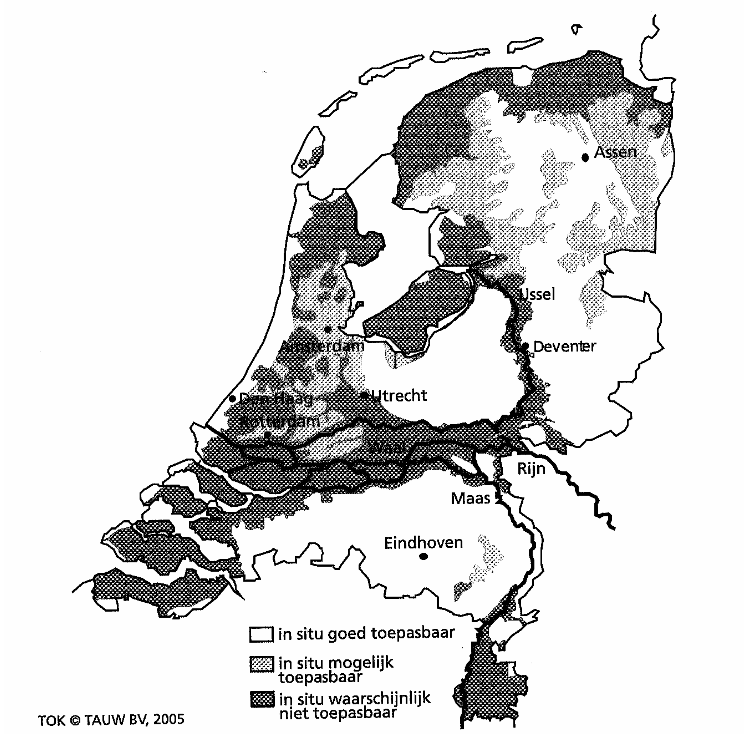

Figure 3. In situ map of the Netherlands (Tauw, 2006)
In situ goed toepasbaar = In situ suitable to apply
In situ mogelijk toepasbaar = in situ possible to apply
In situ waarschijnlijk niet toepasbaar= in situ probably not applicable

Another factor in Sweden that differs compared to the Netherlands is the presence of crystalline bedrock and the relatively shallow soil depths that are common in Sweden. Eskers are common geological formations in Sweden deposited on fractured bedrock, and contain well sorted, high permeable soils. Below the highest coastline these eskers are often connected which means that transport of groundwater is easy over long distances in the formations. DNAPLs released into the ground are therefore easily transported through the permeable material in the eskers and can penetrate deep in the groundwater table and reach the bedrock. This may lead to pollution situations that may be very complicated to remediate.

[23] Pijls, C.G.J., *et.al* (2006)
[24] Witteveen+Bos (2007-04-24)

The literature about performing in situ techniques in fractured bedrock is limited. In the Netherlands fractured crystalline bedrock does not exist, and therefore the experience of performing in situ methods suitable for such conditions is negligible. However, groundwater flow and the conditions for injection and flushing in high fractured bedrock are similar with those in an aquifer of sand and gravel[25].

Even though the geological conditions in Sweden in general are more complex than in the Netherlands, there are cases studied in this project where the geological conditions are not a limiting factor for the applicability of the in situ remediation techniques.

In general there are no geological limitations to apply the new in situ remediation techniques in Sweden. The site-specific conditions vary greatly between different sites throughout Sweden and determine if the techniques can be applied. These conditions must in each specific case be taken into consideration.

4.2.2 Geochemistry

pH is an important factor for the biological activity. The optimum for bacteria growth is between a pH of 5,5 and 7,5. The limit of growth is for most bacteria between pH 4 and 8[26].

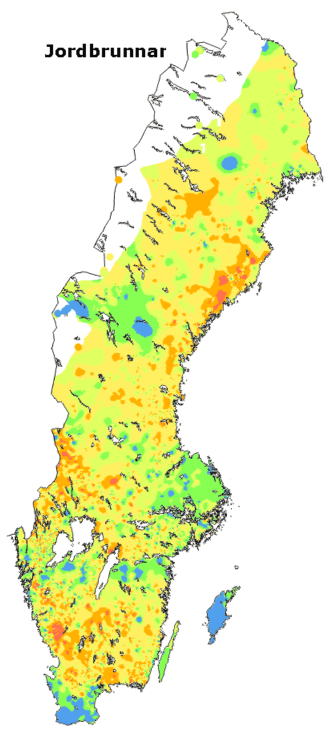

Figure 3. pH in soil wells in Sweden (Markinfo, 2007)

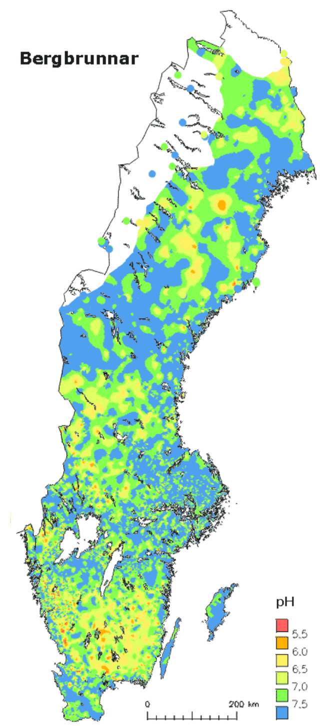

Figure 4. pH in wells drilled in bedrock in Sweden (Markinfo, 2007)

Due to the dominating geological conditions the groundwater in the Swedish soils is characterised by a rather low pH. Most groundwater in soil has a pH slightly below 7 and has a low pH-buffering capacity. Figure 3 and 4 shows that pH and buffering capacity is generally higher in groundwater originating from bedrock[27]. In general the geochemical conditions in Sweden are not a limiting factor or the application of the new techniques described in this report. Low pH is especially a suitable environment for the in situ techniques base on

[25] Domenico. P (1997)
[26] Pijls, C.G.J., *et.al* (2006)
[27] SGU (2007-04-09)

chemical oxidation. The geochemical conditions should be investigated at each specific site, whether they are suitable or not for application of a certain technique or not.

4.2.3 Climate

Climate is considered to be a limiting factor on the applicability of in situ remediation techniques. Climate has mainly impact on the efficiency of in situ techniques involving biological processes, in which the rate of activity decreases with a factor 2 to 3 by each temperature decrease of 10 degrees. The optimum for micro-organisms is by 20-30°C. Also chemical processes are affected, as they slow down at lower temperature. In the Netherlands the ground temperature varies between 10 and 13 °C[28]. Measurements in shallow groundwater temperatures show variations in over the year between 8 and 15 °C. At a depth of approximately 10 meters, the temperature stabilises towards 11°C[29]. The groundwater temperature in Sweden varies normally between 3 and 8 °C [30]. Most in situ methods can be applied in a colder climate, but due to the slower processes, treatment duration will be longer in Sweden than in for example the Netherlands. A raise of the ground temperature hereby leads to stimulation of the biological degradation processes. Lower ground temperatures, as well as seasonal variations have to be taken into account when estimating the duration of the treatment.

4.3 Remediation policy and remediation goal

The chance of success is an important aspect to consider when selecting suitable remediation technique. A successful achievement of the environmental goal does not only depend on the environmental criteria as previously discussed, but also on the remediation policy and the goals themselves.

The development of remediation goals of a specific site is dependent on the risk policy and remediation goals established by the authorities. To make the goals more applicable, they are often derived to a measurable remediation goal, which constitutes a basis for evaluation of different techniques. In order to analyse the applicability in Sweden, this chapter therefore describes the reduction potential of the new Dutch in situ techniques identified in this report. In order to investigate possible hinders or opportunities for the new techniques in Sweden, the chapter also describes what different remediation goals are used in Sweden and the Netherlands and how they are applied in practice.

4.3.1 Comparison of Swedish and Dutch risk policy and remediation goals

In Sweden the remediation goal is expressed in a general and a measurable goal. The general remediation goals are based on a previously conducted risk assessment and should secure an acceptable risk level for humans and the environment today and in the future on the polluted site. The general goals should therefore describe what functions a site can have after completed remediation. The measurable remediation goals are the result of the conducted site investigation, other investigations, risk assessment, evaluation of different remedial measures and the general remediation goal. Once the general remediation goals have been established, measurable remediation goals are established by comparing environmental, technical, economical and other aspects of different remedial measures in a risk evaluation[31]. In a risk

[28] Pijls, C.G.J., *et.al* (2006)
[29] Bense. V (2004)
[30] Englöv. P., *et.al* (2007)
[31] Helldén. J., *et.al* (2006)

evaluation the risks at the actual site are compared to the risk reduction different remedial measures can achieve and what is technical and economically possible[32]. Measurable goals can be expressed in acceptable rest concentrations in the soil, groundwater or soil vapor with respect to a certain risk reduction, but also as a reduction of the risk to a percentage level with respect to one or a few critical compounds.

To simplify the risk assessment of a polluted site, guideline values are established. In 1997 the Swedish EPA developed generic guideline values for 36 contaminants or contamination groups in soil, in order to simplify the assessment of the level of pollution and the need of remediation. The guideline values are developed with respect to risks for humans and the environment and are based on models for risk based values developed in other countries, such as the Dutch CSOIL-model which was developed in 1994. The values are dependent on present and future land use of the site, and are established for three different land use classes such as sensitive land use (KM), less sensitive land use (MKM), and less sensitive land use with groundwater use (MKM GV). Branch specific guideline values have also been developed for common contaminants on former petrol stations[33].

It is important to note that guideline values are not the same as remediation goals. The guideline values are primarily intended to be used in assessment of contaminated sites to indicate contamination levels, which do not pose unacceptable risks to humans or the environment. However they can also be used to indicate the degree of contamination on a site, to develop remediation goals and evaluate remediation results[34]. In the Swedish cases studied in this report, a general goal has often been established for the remediation. However it was also common to apply the generic guideline values as measurable goal, indicating an acceptable risk level for present and future land use.

As the generic guideline values are based on a Swedish standard soil, they are developed to be applicable to many, but not all sites in Sweden. In some cases the generic guideline values as remediation goal can be technically and economically difficult to achieve. An example is the remediation of a PCE-contaminated site in Lerum (case study 1). The general goal was to reduce and preferably abate existing contamination under the building. The measurable remediation goal was to reduce the concentrations in soil and groundwater corresponding to the generic guideline values for less sensitive land use with groundwater protection (*MKM GV*)(soil 20 mg/kg. ds, and groundwater 0,004 mg/l). After three years of in situ remediation with steam injection, soil vapor extraction and pump & treat of groundwater, the measurable remediation goals were not achieved. A new risk assessment and following cost-benefit analysis was conducted.

When the generic guideline values can not be applied, site specific values are developed, taking into account the site-specific conditions in the risk assessment. However Helldéns survey shows that the most common remediation goal applied in Sweden has been the generic guideline values (70%), while site specific values has been applied in 15% of the remediation operations[35]. Experiences from practice indeed tell that in cases where site specific values have been developed and site specific risk assessments have been carried out, the authorities

[32] Andersson-Sköld. Y., *et.al* (2006)
[33] Swedish EPA, report 4889 (1997)
[34] *Ibid.*
[35] Helldén. J., *et al* (2006)

may still be sceptic and demand remediation to general guideline values, because the site specific values are considered as too high[36].

Risk based remediation goals are also applied in the Netherlands. For a large number of substances, *target* and *intervention values* have been established. Target values are derived from the background concentrations and represent a multifunctional soil, while intervention values are based on risks for humans and the environment and represent a seriously contaminated soil. The Dutch intervention values are always related to the percentage of organic material and clay in the soil and are therefore always adjusted to the specific properties of the soil at each specific site[37].

If soil contamination was caused after 1987, a total cleanup until target value has to be done. If the soil contamination was caused before 1987, the contamination still has to be managed and if a site is seriously contaminated then a clean up might be necessary.

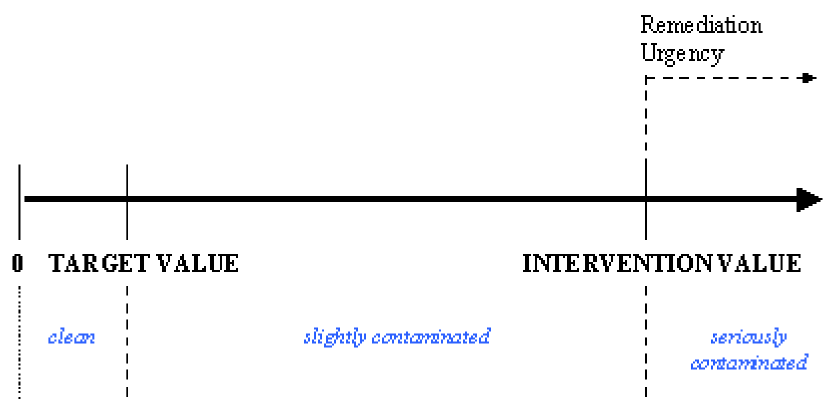

Figure 5. Dutch target and intervention values (CLARINET, 2000)

Figure 5 schematises the Dutch target and intervention values as part of a general framework of risk-based environmental quality objectives. If target values (T) are met, the soil is considered clean and poses no risks to humans or the environment. If the average concentration in a minimum soil volume of $25m^3$ (or a minimum volume of $100m^3$ of pore saturated soil volume in the case of groundwater contamination) exceeds the target value soil is considered as slightly contaminated. If the concentrations exceed the intervention value (I) the site is considered to be strongly contaminated and the seriousness and urgency of the remediation has to be determined. If it is demonstrated that the concentrations are higher than (I+T)/2 for more than one of the substances the soil is considered as moderately contaminated and an additional investigation must be carried out in order to estimate the actual exposure[38].

The interval between target value and intervention value allows residual contamination in the ground with restrictions on land use[39]. In Sweden this interval do not exist and the contamination exceeding the guideline value are normally remediated. Even though Swedish generic guideline values are only recommendations and not legally enforced standards used

[36] Randborg. R (2007-03-16)
[37] Clarinet (2000)
[38] Prokop.G., *et.al* (2000)
[39] VROM (2000)

for risk assessment, experiences from practice is that the values are interpreted as absolute remediation targets and are often equalised with remediation goals[40].

In the Dutch soil policy a distinction is made between mobile and immobile pollution situations[41]. This has major influence on what approach is applied to remediate the contamination. In case of an immobile pollution situation the contamination should be remediated in a function oriented and cost-effective way. For mobile pollution situation the focus is on avoiding further spreading. The Dutch government realised that complete removal of mobile pollution is often technically or economically impossible to realise. The remediation result in this kind of situation is therefore expressed in terms of stable and environmentally acceptable end-state[42]. Hence in cases where there is no or little environmental risk the remediation goal is not focused on a target concentration, but instead on reaching a situation where the plume is not growing and/or moving[43]. Monitoring is therefore an essential instrument when remediating mobile pollution in the Netherlands.

In the Netherlands the remediation target values are adjusted in respect with content of organic material and clay on each specific remediation site. An example of adjusted values is given for the case study Oosterhout (case study 9). Table 4 shows some of the Swedish generic guideline values and the Dutch target and intervention values. The Dutch intervention values adjusted to Swedish standard soil with 2% organic coal are also depicted. This table shows that when adjusting the Dutch values to the organic material in a Swedish standard soil containing 2 % organic coal (3,4% organic material) the average value, (I+T)/2, do not differ much from the Swedish generic guideline values.

Table 4. Swedish generic guideline values, Dutch intervention values and Dutch intervention values adjusted to a Swedish standard soil

	Swedish generic guideline values[1]			The Dutch intervention vales[2]		Dutch intervention values adjusted to Swedish standard soil with 2% organic coal		
	mg/kg.ds			mg/kg.ds (2)				
	KM	MKM GV	MKM	Target values	Intervention values	Target values	(I+T)/2	Intervention values
Benzene	0,06	0,2	0,4	0,01	1	0,003	0,17	0,34
Toluene	10	35	35	0,01	7	0,003	22	44
Ethyl benzene	12	50	60	0,03	4	0,010	8,5	17
Xylene	15	60	70	0,1	0,2	0,03	4,3	8,5

[1] Swedish EPA and SPI, report 4889. Values are expressed as the concentration in a Swedish standard soil (2% organic coal)

[2] VROM, 2000. Values are expressed as the concentrations in a Dutch standard soil (10% organic material and 25% clay) (The relation between organic material and organic coal is a factor of 1,7).

The Dutch cases studied show that in practice different remediation goals are established depending on land use and when the contamination was caused. At the oil depot in Markeloo

[40] Kemakta Konsult AB (2002)

[41] The mobility of contaminants is determined by local soil conditions, *e.g* acidity, level of oxidation/reduction potential and bonding capacity.

[42] VROM (1999)

[43] SKB, Praktijkdocument ROSA (2005)

and oil pumping station in Oosterhout the average value (I+T)/2 were applied. The case studies further demonstrate how the focus of soil remediation projects in the Netherlands often is on more general goals such as cost-effective remediation and to achieve a stable end situation within a time frame of 5-30 years.

The Dutch and the Swedish remediation values were established at different occasions. Since the first Dutch risk-based remediation values were developed in 1994 (A, B and C-values), several re-examinations have been done to keep them up-to-date with the widened knowledge in risk management and the properties of different contaminants. For some compounds this has lead to an acceptance of higher concentrations and for others to lower concentrations. In Sweden the values developed in 1997 are still being used and have not been revised according to new knowledge. The Swedish values are in need of upgrading[44]. The out-of-date values in Sweden can be one reason to the differences to the values applied in the Netherlands.

4.3.2 Analysis with respect to reduction potential of the new techniques

The potential of a technique to reduce the concentrations of one or several different compounds in soil, soil vapour and groundwater is dependent on several different aspects, not the least the environmental conditions at a site as described in 4.2. What aspects are critical is different for each specific technique and the abatement mechanism it is based on. The reduction potential is also dependent on the features of the different compounds such as age, initial concentrations, spreading and phase distribution. All these aspects are simply unique for each specific site. Lab- and pilot-test are therefore critical parts in the planning of the remediation in order to decide the site-specific reduction potential of an in situ technique. Other critical aspects determining the reduction potential are related to the installation and the running of the remedial equipment. These aspects have not been described in this report, but are nevertheless important to take into consideration in the preparations, execution, maintenance and evaluation of the results.

Table 5 shows an overview of the residual concentrations down to what the different in situ remediation techniques have potential to decontaminate. Reduction potential is indeed site specific as discussed above, and any exact values are therefore possible to acquire.

Table 5. Overview of the residual concentrations in soil after applying the Dutch in situ technique, expressed in terms of Dutch remediation values

Technology	Residual concentrations corresponding values
Surfactant/ Co-solvent flushing	Depending on soil and contamination
C-sparge	>Intervention value
Perozone	>Intervention value
Six-phase heating	Target values
EBIS	<Average value
EBR	Target values
Liner®	>Intervention

[44] Kemakta Konsult AB (2002)

The reduction potential of the new in situ techniques identified in this report corresponds to values between the Dutch average and target values. Thus, at suitable environmental conditions, the techniques have potential to reduce contamination levels corresponding to acceptable risk levels in Sweden.

5 Identification of opportunities and barriers to innovative in situ remediation techniques

In previous chapters, new in situ techniques where identified and the applicability in Sweden was analysed. A conclusion that can be drawn is that several techniques that are commonly applied in the Netherlands have already been tested or demonstrated in Sweden, but without leading to any further applications. This raises a question leading to the second part of this thesis: why are innovative in situ techniques more commonly applied in the Netherlands than in Sweden?

At IBC's 10th Conference of Contaminated Land Bardos *et al* (1999) emphasise the importance of making a distinction between the technical "suitability" and technical "feasibility" which can be described as the theoretical fit and practical fit respectively of a remedial solution. The feasibility of a proposed solution may be heavily dependent on a range of non-technical issues and subjective perceptions. In order to stimulate development and use of new in situ techniques in Sweden, possible barriers and opportunities must be identified. By comparing the remediation work in Sweden and the Netherlands some of the most important barriers and opportunities are identified in this chapter.

5.1 Technical factors

5.1.1 Overall strategy

In situ techniques typically remove, destroy and/or transform contaminants. They can be applied for source reduction, plume reduction or both. Apart from suitability for the actual contaminant and soil conditions, aspects like concentration range and phase distribution must be regarded to be able to select an appropriate remediation technique. A combined approach may be applied in order to achieve the remediation goal in the most efficient way[45]. This is especially important to consider where chlorinated solvents are the main pollution, since these are often sinking deep into the groundwater zone or spreading in a large contamination plume. In these situations it may not be technical or economically feasible to apply the same technique to treat source and plume areas.

Noteworthy in the Dutch cases is that different techniques are often combined to remediate source- and plume areas respectively, while in the Swedish cases this was not common. In the Swedish cases no clear distinction was made between source and plume area. In the Dutch cases excavation or in situ chemical oxidation were applied for source areas where high concentrations are encountered. Pump & treat is commonly applied to remediate the part of the plume close to the source where moderate concentrations is present and sparging methods or soil vapour extraction of the plume where lower concentrations of dissolved contamination were found. This is expected to be the most cost-effective solution to reduce contaminations to acceptable levels.

In the compared case studies a combined approach to remediate the different phases of a contamination is common in both Sweden and the Netherlands. Most common in the Swedish cases is to combine soil vapour extraction for contaminants in the unsaturated zone and pump and treat methods for the saturated zone. Where free phase contamination is present in the

[45] Bardos *et al.* (2000)

Swedish cases, no special treatment is carried out, while in the Dutch cases free phase is remediated by excavation or by multiple phase extraction.

In four Swedish cases the remediation goal was not reached and three of the remediation operations had to be completed with excavation. This is a rather interesting difference to the Dutch cases, where excavation already is part of the remedial plan in a combination with in situ techniques. There are cases that are still not completed when this investigation is carried out which should be taken into consideration in this discussion. Common follow-up actions in the Dutch cases are groundwater extraction or multiphase extraction.

Several suggestions may be raised to explain the above-described differences in applied overall strategy:

1. In difference to most Swedish cases, the release of pollution to the ground comprised larger volumes in the Dutch cases and the permeable soils lead to deep contamination or large contamination plumes. Excavation of the entire contaminated volume would not be technical or economically feasible.

2. The Dutch remediation goals are often expressed in terms of topsoil and sub soil or unsaturated and saturated zone, source remediation and plume remediation in order to achieve cost-effective remediation (see 3.3.2). The goal is to reach a stable end state of the contamination plume within a time period of maximum 30 years. The long time frame opens up for the opportunity to apply more extensive techniques for remediation of the plume, such as monitored natural attenuation. Such a difference is not often being made in the Swedish remediation goals.

3. The selection of a relevant solution such as a combination of different techniques for different treatment of saturated-/unsaturated zone, free phase, solid phase, liquid phase or gaseous phase, source or plume area requires an adequate site investigation. This will be further discussed in chapter 5.1.2.

The typical example of a Dutch approach of removing mobile pollution in the subsoil has been to[46]:

- remove the source area and the near plume area as far as possible by applying an intensive remediation technique such as excavation of the unsaturated zone and in situ chemical oxidation in the saturated zone;
- remove the near plume cost-effectively by pumping up the contaminated groundwater and cleaning on site until ‘stable end situation’ is reached;
- apply an extensive remediation technique, such as natural monitored attenuation for cost-effective removal of the plume;
- regularly monitoring to follow the influence of the treatment installation;
- Aftercare such as reporting the quality of the soil/groundwater on the site, monitoring or active measures. Monitoring and aftercare is discussed further in chapter 3.3.6.

Utrecht, Markelo and Hilversum (case studies 6, 7 and 10) are good illustrations of how different techniques are combined in the remediation. In Utrecht chemical oxidation is applied

[46] VROM (1999)

in the source area, co-solvent flushing together with pump & treat on the part of the plume closest to the source, while the plume will be monitored during the entire remediation. Monitoring of source, transit area and plume will continue during the next 15-30 years. The after care in this case consists of the administrative establishment of the final ground quality (reporting).

In Hilversum the remediation was focused on removal of the source contamination and the transit area. Excavation and in situ chemical oxidation of source areas in combination with pump & treat with infiltration is applied. In case of hot spots where chemical oxidation is not sufficient, the strongly contaminated soil will be excavated by deep drilling. What remediation measures to be taken for the plume is decided at a later stage.

5.1.2 Site investigation

"Any remediation approach, whether in-situ or ex-situ, can only be as good as the site investigation on which it was based"

– Bardos. R. P. (2000)

An adequate site investigation is of significant importance when making risk assessment and defining appropriate remediation goal of a polluted site and when evaluating the suitability of a technique to remediate a specific pollution. The risk assessment and the evaluation of the suitability of a technique are based on the quality of the available information about the site. Therefore an adequate site investigation is one factor that can significantly enhance the accuracy of forecasting remediation costs, by providing necessary information to optimise the relevant solution.

To select effective remedial solution knowledge about the distribution of present contaminants and the ground characteristics need to be purchased. What strategy is applied to purchase this information depends on assumptions based on previous knowledge about for example the type of contamination, type and extent of sources, released quantities, the location of the release and availability and quality of the ground conditions. Last but not of least importance is the available budget for the site investigation. However, all procurement of services such as site investigation, needs to be done with a view to value and confidence in achievement of objectives, not cost (CLARINET, 2002).

It is a complicated task to compare the Swedish and Dutch cases in order to find how differences in conducted site investigation have impacted the selection of new in situ techniques or the success of the chosen solution. The documents used for this study give too scarce information on this topic to be able to make a relevant comparison between the Swedish and Dutch cases.

Table 6 summarises the number of samples analysed in the Swedish and Dutch cases. The Swedish cases are dominantly petrol stations where the most common sources are leaking underground tanks or pump stations leading to smaller contaminated volumes. The Dutch cases are on the other hand mainly sites where larger quantities of petroleum products have been released into the ground, for example oil depots and fuel pumping station. The release of contamination into the ground has been in larger quantities due to rupture of pipes, or by spill from several sources leading to much larger contaminated volumes than in the Swedish cases. This probably explains why much more sampling points where made in the Dutch cases.

Table 6. Number of sampling points and analysed samples in Swedish and Dutch cases

Case	Activity	Assessed contaminated volume	Number of sampling points	Number of analysed samples
Arvehäll	Dry cleaning	-	-	21 soil, 3 gw
Götene	Petrol station	-	19	3 soil, 1 gw
Haninge	Petrol station	3000	14 drillings, 7 gw wells	only gw
Bottnaryd	Petrol station	650	13+25	9 soil, 2 gw
Boden	Petrol station	600	10	5 soil samples
Utrecht	Metal degreasing	60435	-	13 soil, 26 gw
Markelo	Fuel depot	90000	-	55 samples
Ermelo	Fuel loading station	650	three deep drillings	three deep drillings
Oosterhout	Oil pumping station	24750	76	71 gw, 33 soil
Hilversum	Gas factory	8750	-	100 samples
Gent	Oil refinery	60000	-	25 gw, 10 soil samples

A common reason to failure of the in situ operations in Sweden seems to be insufficient site investigation. For example in Arvehäll (case 1) the source area was not properly located and residual free phase contamination was still expected to be present in the ground after terminated in situ operation. The residual contamination was expected to give rise to continued spreading of dissolved and volatilised contamination after the remediation. In this case no back-up plan was established when the in situ operation was terminated, new measures had to be considered including balancing the benefits of taking further action. The petrol station in Haninge is another example of where the in situ remediation did not succeed partly because the contamination was found much larger than encountered in the site investigation.

5.1.3 Implementation

The success of a remedial operation in practice is dependent on the implementation of the technique. The implementation for in situ treatment techniques differs from operations where excavation and ex situ methods are applied. Since the features between sites may differ it is not adequate to in detail compare practical examples of implementation of in situ remediation techniques. Therefore this chapter is aiming to point out general differences in implementation between Sweden and the Netherlands and analyse how they affect the use of new in situ techniques.

Implementation encompasses the process of applying a remedial approach to a particular site and involves[47]:

- Planning and remedial operations;
- Regulatory acceptance and licensing of a remedial plan;
- Site management;
- Verification of performance;
- Monitoring process performance and environmental effects;

[47] Clarinet (2002)

- Public acceptability and neighbourhood relationships
- Strategies for adaptation in response to changed or unexpected circumstances
- Aftercare

The issues of site management and public acceptability and neighbourhood relationships are not discussed in this chapter.

Planning, regulatory acceptance and licensing of remedial plans

Before the remediation phase can be started the remediation plan has to be approved in consultant with the authorities. Hence the remediation plan is an important document in both Sweden and the Netherlands. In the Netherlands a checklist of what a remediation plan should contain is described in the ROSA document. Important items in the Dutch remediation plan are:

1. The formulation of the goals, fallback- and change criteria in the remediation process
2. Monitoring of remediation process
3. Organisation, communication and guarantee issues of the remediation

In the Netherlands the contractor is more often involved in the drawing up of the remediation plans. The contractor often contacts the consultant to help out with drawing up the remediation plan. There are three general differences found between Swedish and Dutch remediation plans:

1. <u>Supervision.</u> The Dutch remediation plan always contains a detailed description of how the supervision of the remediation process will be performed. This chapter considers issues such as: verification; sampling of soil and groundwater; analyses; and evaluation.
2. <u>Monitoring.</u> Monitoring can be a part of the program for the supervision. This chapter contains monitoring strategy-, and a measuring programme it also contains a description of risks for failure in the remediation process and how to act in case of failure i.e. a fallback scenario. This will be described separately in this chapter.
3. <u>Aftercare.</u> Dutch remediation plan normally contains a description of what care activities will be carried out based on the present knowledge of the pollution situation. Aftercare will be discussed in a separate part in this chapter.

Verification and monitoring of process performance and environmental effects

Monitoring is an important part in remedial operations where in situ approaches, in order to follow the remediation progress: to maintain measure and evaluate the progress and if needed make necessary adjustments to optimise the remediation.

Monitoring is used in two aspects:

1. Process monitoring to control that the system functions well and stimulates the processes in the ground.

2. Performance monitoring in order to evaluate the results.

To make a successful monitoring program, good knowledge is required about the starting situation. In the Netherlands monitoring is an important component in the standard approach of remediation mobile contamination in the subsoil[48]. Yvonne Österlund, contaminated land co-ordinator at Swedish EPA, explains that long term monitoring programs are being avoided as far as possible in public funded projects in Sweden. The Swedish EPA has the commission to prioritise which contaminated sites will be remediated with governmental funds. Grants that are rationed to the Swedish EPA from the government are based on political priorities and allotted on a yearly basis. Therefore it is difficult for the Swedish EPA to guarantee funding of long term monitoring programs.

In private funded projects, Österlund further explains, it is the problem holder who must suggest a monitoring program, which the authority can accept. However, problem holders in Sweden do not often suggest long-term monitoring programs, but expect that these can be avoided[49].

Kjell Färnkvist, senior advisor at the Swedish EPA[50], tells that a common problem with in situ remediation in Sweden is to decide when the remediation goals are reached. Jonny Bergman[51] is working at the soil remediation contractor Soilrem MB Envirotech in Sweden. According to Bergman are discussions common during the remediation considering when it is clean enough and what remediation result is reasonable. This is often a discussion between the contractor and the advisor.

Martin Veul[52], senior advisor at the soil and groundwater department of Witteveen+Bos in the Netherlands, explains that in the Netherlands the authorities stress the importance of quality in supervision. In practice it is a continuously on-going negotiation between the advisor and the authorities to decide when the remediation can be considered as finished.

Fall back scenario

It is common that the Dutch authorities ask for a fallback scenario. Possible risks with the chosen solution are identified and fallback criteria are defined. Depending on the goal of the remediation, a back up plan is designed. The fall back scenario is part of the remediation plan to avoid unexpected surprises in case of deviant results and activation of the fallback scenario[53].

Aftercare

In the Netherlands it is accepted that functional and cost-effective remediation leaves residual contamination in the soil and groundwater[54]. Therefore after care is today a fix component of the remediation in the Netherlands. Aftercare is started when the goals of the remediation have been achieved. The first version of the aftercare plan is normally a part of the remediation plan. The care plan has two purposes:

- to report that there is a residual pollution present and that there may be restrictions on land use.
- to ensure that the remediation goals are maintained

[48] VROM (1999)
[49] Österlund. Y (2007)
[50] Färnkvist. K (2007)
[51] Bergman. J (2007)
[52] Veul. M (2007)
[53] SKB, Praktijkdocument ROSA (2005)
[54] VROM (1999)

After care can consist of either registration, monitoring (in situations where spreading is still possible) or active measures.

5.2 Social factors

Even though a remediation technique may fulfil the technical requirements at a site it might not be feasible. Bardos *et al*. (2002) means that it is important to make a distinction between these two aspects, because the feasibility of a proposed solution may be heavily dependent on a range of non-technical issues and subjective perceptions[55]. This chapter describes some main differences between Sweden and the Netherlands with regard to non-technical factors that influence the decision of applying a new in situ technique. These non-technical issues and subjective perceptions are based on policies and rules established in our society, and are therefore described as *social factors* in this report.

5.2.1 Decision making and decision making criteria

There are a number of factors that need to be considered in selecting an effective remedial solution. In addition, it is also important to consider the manner in which a decision is reached[56]. In order to overcome existing implementation barriers, knowledge is required on the decision-making processes and the criteria, which lead to the selection or rejection of specific remediation techniques. Through present questionnaire and case studies these criteria and processes were identified. Case studies are found in appendix 5.

Tools for decision making

In Sweden it is compulsory to identify and suggest alternative solutions in remediation projects financed by the Swedish EPA. Systematic risk management is part of the handling of contaminated sites, in particular regarding governmental funded remedial sites. Investigation of remediation measures alternatives to compare different remediation alternatives considering different criteria and risk evaluation are two examples of tools. These tools and the different steps of risk management are described in a quality manual published by the Swedish EPA[57]. The responsible party, their consultants, authorities, and the national environmental protection agency should use the manual. Following a risk assessment, remediation goals and a suggestion of remediation measure alternatives are proposed. The suggested remediation measures should meet some basic criteria, principles and norms required by the Swedish EPA. The selection of new in situ techniques may be affected by some of these requirements as listed below.

- *Best available technique should be applied as long as it does not involve unreasonable costs. Energy saving technology should be used as far as possible;*
- *The measures should be of one-time character;*
- *The measures should not other than in a period of transition involve maintenance and care after completed remediation;*
- *Measures should be performed so that the planned land use will be little as possible restricted;*

[55] Bardos *et al.* (2002)
[56] Clarinet (2002)
[57] Swedish EPA (2003)

- *Measures should be performed in a manner that no risk for need of further remediation of the site will be required; and*
- *Sites remediated with public means should state as a good example to remediation carried out by others*

The requirement on best available technique and energy saving technology could be in favour to new in situ techniques, when sufficient and quality data is available to compare with conventional techniques. One of the advantages of in situ techniques is typically the reduction of transports and thereby also energy. There are exceptions where this is not true in as the use of energy to run the operational equipment such as pumps and electrical heating installations can lead to high energy consumption. One example where the energy consumption was very high is the remediation in Markelo (case study 7), where the cost of energy was up to 100.000 Euro/year. These are aspects that can be balanced in an evaluation. The requirement of solutions of one-time character may be a limitation to an increased use of new in situ techniques as they are struggling with uncertainties about the efficiency and how to verify its performance. Because of these uncertainties residual contamination may be left behind in some cases, leading to further spreading of pollution and new remediation operations or care activities after the finished remediation. However, this problem should not only be addressed to in situ techniques. Residual contamination can also be left behind when using conventional excavation, as the site investigation may not have discovered all source areas on a site, or the contamination occurs under constructions, where excavation do not reach the contaminated soil. As sites remediated with public means should statue as good example, new in situ techniques are often not applied in those kinds of projects due to the named uncertainties. As the Swedish EPA normally finances the most serious cases, which are often of larger scale, they only accept techniques of which there is more experience[58].

However, there is a risk that the benefits of using new techniques are not fairly identified as all the named requirements are not considered in investigations of remedial solutions. This favours more traditionally applied techniques.

In the risk valuation different remediation alternatives are compared to each other considering environmental, technical, economic and other aspects in relation to the risk reduction. This is important in order to make the process and the basis for the selection of measures more transparent[59]. Other aspects include for example overall environmental impact, general and individual interests, public risk perception. The alternative involving best available technique (BAT) as well as the 0-alternative[60] must be investigated. The manual provides a description of what should be included in the technical description. However there is no information about how to describe general and individual interests or other none technical aspects, such as the overall environmental impact, as well as what needs to be included in cost estimation[61].

In Sweden there is no corresponding guidance for private funded remediation sites in risk management and balancing different remedial alternatives. Experience from the branch is that the decisions of remediation technique are often irrational[62]. The questionnaire also shows that sustainability considerations and cost-benefit analysis does not have a great impact in the decision. However, people from the remediation branch confirms that it is becoming more and

[58] Lindsköld. R (2007-03-20)
[59] Andersson-Sköld. Y., *et. al* (2006)
[60] The 0-alternative encompasses the alternative in which no measures are taken
[61] *Supra* note 39
[62] Bergman. J (2007)

more common to consider more non-core criteria such as environmental impact by transports in the risk valuation.

Changes in the Dutch remediation policy in 1997 implied consideration of the relative environmental merits of the remediation procedures and the remediated site, allowing for a lower degree of remediation if the impact by the remediation procedure is "environmentally costly". The primary factors driving decision-making in the Netherlands are the benefits in terms of fitness for current or future use. Environmental benefits (less aftercare, less environmental impact), cost and technical feasibility are factors which also are considered[63]. Tools for selection of appropriate techniques are From funnel to sieve, Doostart A5 and the ROSA practical document (available at the SKB website). These documents are handbooks, commonly used by provinces, municipalities and problem holders to simplify the selection of cost effective and robust remediation measures and when establishing reasonable and acceptable remediation goals. In the ROSA document it is suggested to value positive and negative effects by a specific remedial solution with + and – respectively in simple cases, while for more complex cases it is recommended to conduct a multi-criteria analysis[64]. An example where a simple cost-benefit analysis on the basis of the ROSA document was used in the selection and motivation of remediation measures was the remediation in Oosterhout. The provincial authorities demanded a cost-benefit analysis on the basis of the ROSA document to be conducted. Table 7 shows the evaluation matrix with the evaluated techniques. In situ chemical oxidation together with peroxide and soil vapour extraction for treatment of the source area and air stripping of the plume area were finally selected. The main motivation was the short duration and the low price.

Table 7. Evaluation matrix of remediation techniques in Oosterhout

Technique	Duration	Costs	Suitable for actual pollution		
			source	transit	plume
Pump&treat	--	-	++	+	-
2/3 phase extraction/ SVE	+	+	++	+	--
Compressed air injection (stripping)	+	+	++	++	++
Steam injection	+	-	+/-	-	--
In situ bio restoration	-	+	+/-	+	++
Excavation	++	--	++	-	--
Chemical oxidation	++	+/-	-	+/-	+/-

Using these manuals leads to confidence of the different stakeholders in the decision process and the results of the remediation.

In the Netherlands the REC decision support system, which involves weighting of the various remedial alternatives, has been developed. The system enables objective mutual comparison of the different remediation technologies, their contribution to risk reduction, environmental merit and cost. The term "environmental merit" is used to describe non-core environmental effects of a remedial activity (Nijboer, 1998) [NOBIS 1995 a&b] (available at www.skbodem.nl/projecten/nobis1]. However, the REC system was not applied in any of the Dutch cases studied in this investigation.

[63] Clarinet (2002)
[64] SKB, praktijkdokument ROSA (2005)

Decision making criteria

Experiences from the Swedish case studies show that total cost is the most important criteria when selecting remedial solution. The cost issue is analysed and discussed in a separate chapter (see costs-effectiveness). The in situ solutions are also selected in cases where the contamination is present under buildings. Another important criterion was that the remediation would have as little impact as possible on the on-going activity and in situ solutions were in these cases a better alternative than solutions involving excavation. The environmental impact had minor influence in the selection. Bottnaryd is the most recently performed remediation operation (2005) and due to the ongoing activity, the duration of the operation was also an important criterion in the evaluation. This was the only studied case where other techniques were included and compared in the evaluation, while in the other cases the in situ solution was compared with total excavation. In some cases in situ was selected because excavation was not an alternative. Important to note is that in most of the Swedish cases the in situ techniques applied were new experiences to the problem holders.

The case studies show that it is not common practice to make a proper analysis of environmental costs and benefits of the different remediation alternatives suggested in a solution to clean up a contaminated site. It is more common to select in situ technique because it is perceived to have less negative environmental impact than solutions involving excavation and transport.

In three of the six Dutch cases, other techniques than the ones finally selected where evaluated. Cost-benefit analysis was performed in two cases on demand from the authorities. In Utrecht and Markeloo a decisive factor in the choice of technique was the good experience the problem holders had of the selected techniques from other sites. In situ solutions have been applied where excavation has not been viable because of bad access to the source area, deep contamination, or disturbance of on-going activity should be as limited as possible. The total price is another important factor leading to the decision of a solution involving in situ techniques. In situ solutions with chemical oxidation have been selected in cases where duration of the operation and the reliability of the solution are important criteria.

5.2.2 Cost-effectiveness

A conclusion from earlier chapter is that costs and cost effectiveness is one of the most decisive criterion when selecting remedial solution for polluted sites in both Sweden and the Netherlands. Cost-effectiveness is typically expressed as the ratio of change in costs to the change in effects. In the field of soil and groundwater remediation this can be expressed as the difference in cost between different remedial solutions in relation to the achieved benefits. Factors that affect the cost-effectiveness are the potential to reduce the cost of remediation and/ or increasing the value of land[65]. Normally this could be achieved by reducing the volumes of soil needing treatment and by increasing the proportions of materials to be recycled and reused. To provide a clear view of the value of a remediation investment, and to enable comparison between different remedial solutions a cost benefit assessment can be performed. In this chapter aspects regarding costs and cost-effectiveness will be presented.

[65] Clarinet (2002)

Incentives

An incentive is any factor (financial or non-financial) that provides a motive for a particular course of action, or count as a reason for preferring one choice to the alternatives. The majority of persons answering the questionnaire claim that the financial incentives in Sweden to use innovative remediation technology are nearly negligible. Low costs are suggested as the main motive to try new techniques. Martin Veul at Witteveen+Bos claims that this is also the situation in the Netherlands. Before new techniques are selected they have to be proven better and cheaper than the more conventional alternatives. However, there are no incentives for the Dutch government to promote certain techniques before others[66].

Indicative costs of remediation

The prices for applying different remedial solutions may differ between countries and lead to differences in cost-effectiveness and hence the use of new techniques. Table 8 shows typical prices for ex-site treatment and landfilling in Sweden and the Netherlands.

The price information has been compared with prices reported by CLARINET (2002). The price levels for Sweden are in Clarinets report higher than the actual price levels of today for ex situ treatment. This shows a decrease in price levels for ex situ treatment in Sweden. An increasing establishment of treatment plants in Sweden during the last few years leading to low prices can explain this[67]. According to this information, ex situ treatment of contaminated soils are in general more expensive in Sweden than in the Netherlands. There is also a considerable price difference between the countries regarding price levels of landfilling of contaminated soils. In the Netherlands landfilling is in general more expensive than off site treatment. During The last 10 years the price levels for landfilling in Sweden has been reduced by approximately 100 Euro per tonne and today it is in many cases much cheaper to dump contaminated soils on a landfill than to treat them off site. One reason to the reduced price levels is the increasing need of covering materials at the many landfills that are closing down due to a new landfilling directive in 2004[68].

A difference that should be noted is that The Netherlands adds an environmental tax on the landfill fee, ranging in size dependent on the specific weight of the material. This makes landfilling an even more expensive alternative and in situ remediation is in many cases a cheaper alternative than landfilling. Besides this, landfill is only allowed in the Netherlands if it can be proved that no other solution is technically or economically possible. This rule is very strict and a special permit must be applied for, giving allowance to landfill.

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[66] Veul. M (2007)
[67] Sven-Olof Andersson, SAKAB (2007-04-20)
[68] *Ibid.*

Table 8. Price levels of ex-site treatment and landfilling in Sweden and the Netherlands

Ex situ treatment method- and landfill[3]	**Sweden**[*, 1] [Euro/tonne]	**The Netherlands**[2] [Euro/tonne]
Chemical/physical treatment	36-52	25-35
Thermal treatment, (combustion)	83-260	40-50
Bilogical degradation (landfarming)	26-36	15-30
Landfill	5-52	45-60
Environmental tax	None	14.34-86.91

Notes:
[*]The fee has been derived from Swedish kronor, based on the currency 1 SEK=0,10383 EURO
[1] Price information in Swedish kronor from SAKAB, www.sakab.se (2007-04-20)
[2] Price information from Peter Hoefsloot, Witteveen+Bos (2007-04-20)
[3] Price information does not include transport costs

For new in situ techniques to be selected they have to be cost competitive with conventional techniques such as excavation and landfilling. Table 9 shows the approximately cost for some new in situ technologies in the Netherlands, found at the SKB web site[69].

Table 9. Approximately price levels of in situ remediation in the Netherlands

In situ technology	**Price levels in the Netherlands**	
	(euro/m³ soil)	(euro/tonne)
Flushing with co-solvent or surfactants	Site specific	Site specific
Phase separation fluid pump	Site specific	Site specific
C-spargeTM	Plume: 2-20	6-60
	Source: 20-40	60-100
Perozone	Plume: 2-20	6-60
	Source: 20-40	60-100
Fenton's Reagent	-	-
Six phase heating	20-120	60-300
EBR	Site specific	Site specific
	Source: 50-150	125-375
	Plume: 0.1-10	0.25-25
EBIS	50-150 euro/m² screen	
Liner ®	Site specific	

The figures are expressed in euro/m^3 soil. To get correct figures per tonne, the figures can be multiplied with the specific weight of the soil. In Sweden the specific weight of soil range between 1.5-1.7 ton/m^3. The cost to apply a remediation technique is highly dependent on site specific conditions and therefore the cost-figures in the two tables are only indicative. For this reason it is in some cases not possible to provide general price information. According to Henrik Ekman[70], now active at the contractor Eco Tec performing different in situ methods, the price difference for in situ remediation methods is moderate between different countries in Europe.

[69] SKB Eurodemo (2007)
[70] Ekman. H (2007)

Transport

Transport of excavated soil material can be a significant cost in the total performance of a remedial operation, especially when the distance to a landfill or treatment plant is significantly far. In approximately 1/3 of the cases investigated in Helldéns survey, the contaminated soil volumes were transported between 100-500 km to a treatment plant. This should not only be considered as costs issue, but also as an important factor of negative environmental impact. In the SPIMFAB projects investigated, costs for transport of polluted and clean soils for re-establishment of the site represents in average as much as 14 percent[71]. Hence transport cost as a part of the total cost of a remedial solution, should have impact on the cost-effectiveness, not the least in Sweden.

Benefits

It is important to keep in mind that cost effectiveness is subjective and different stakeholders may perceive it differently as described below.

- ***Landowners*** *or* ***problem holders*** define the project cost effective if the cost to eliminate the problem is less than the value of the problem itself. The landowner seeks for a solution that maximises the value of the land. This also depends on whether the land is seen as a liability or an opportunity[72]. Martin Veul explains that today private actors finance the main parts of the remediation projects in the Netherlands. In such cases the land is seen as an opportunity and is only a small part of i.e. a redevelopment project. Cost is the main issue and the landowner or investor sees very optimistic on the use of new techniques as long as they are competitive with more traditional techniques.

Public companies or municipalities as problem holders are obliged to make decisions that are legal and in the best interest of its members. They are not obliged or necessarily authorised to consider any other factors.

- ***Regulators*** interests are not prioritised by project economics**.** Regulators are obliged to make decisions that ensure health and environmental protection and that are in the best interest of the public[73]. "Best interests" leads to the questions: whose interests, which interest, whose costs, which costs? Martin Veul describes how soil remediation in the Netherlands, after the Lekkerkerk scandal, was strongly driven by public commotion. Environmental protection was of highest priority, which means that the remediation goals were very tough. This led to few remedial operations of polluted sites to be carried out and stagnation in the remediation process. After a while the industry demanded a more flexible remediation policy with the motivation that we have to live with our faults, but not remake our mistakes. Today remediation goals have to be reasonable and the remediation cost-effective. In the long term, this has lead to the less strict remediation goals and increased use of new in situ techniques.

- ***Service providers*** make decisions on technique regarding the landowners defined needs and within the regulatory constraints. Cost effectiveness is measured in exclusively economic units[74]. Jonny Bergman claims that the consultant is the actor who should

[71] Helldén. J., *et. al* (2006)
[72] Clarinet (2002)
[73] *Ibid*
[74] *Ibid*

recommend a solution to the problem holder. However, there are no incentives for the advisor to recommend an innovative technique[75].

According to the questionnaire, experiences from Sweden agree that benefits that could motivate the selection of innovative remediation techniques are mainly connected to cost- and timesavings and environmental benefits when comparing to traditional excavation and transport to landfill. This would be achieved by for example reduced transports and less interference on site. Participants of the questionnaire also suggests that to start applying more innovative remediation techniques would also enable the development of more efficient techniques and counteract a stagnating development.

5.2.3 Duration and time constraints

A factor that normally has influence on the selection of remediation technique is the duration of the remediation operation. However, results from the questionnaire tell that the time aspect in general has low to moderate impact on the decision of remedial solution in Sweden. On the other hand, the factors that often lead to the rejection of new in situ techniques are time constraints and uncertainties of the time perspective. In stead it is uncertainties about the efficiency of new in situ techniques and the time aspects that are important factors influencing the decision of remedial solution. Uncertainty of using in situ techniques in Sweden is often related to the experienced difficulties in deciding when an in situ remediation can be considered as finished[76].

Mikael Karlsson is active at the soil remediation contractor Detox AB in Sweden. Uncertainties about project costs- and duration when involving new in situ methods arise according Karlsson, from limited knowledge about the treatment methods, geology, groundwater conditions and the actual extent of the pollution in the ground[77]. One example is the remediation of the former dry cleaning in Arvehäll. An experience from the remediation was that the estimated time of the remedial operation was too short. The problem holder suggests that in future remedial operations such as this, one should count with longer duration than estimated in this project[78].

Bergman at MB Soilrem Envirotech, claims that the time aspect is the most common reason to why new in situ remediation techniques are not selected in remedial solutions in Sweden[79]. Many projects are under time pressure for one or another reason. Bergman’s experience is that time pressure is one of the most important hinders for the use of new techniques.

The time constraint in remediation projects is often dependent on the designated land use (see 4.2.5). According to the questionnaire the goal of the remediation and the future land use are factors with high impact on the decision of technique. Time constraints are common in city renewal and large building projects and dictate the time frame for many remediation projects. Contamination is seen as a first hurdle to be removed as fast as possible. Time constrains can also result from regulatory pressures. For example when a serious environmental impact from contamination is suspected, solutions are needed that are effective and quick[80].

[75] Bergman. J (2007)
[76] Färnkvist. K (2007)
[77] Karlsson. M (2007)
[78] Bolvede. P (2004)
[79] Bergman. J (2007)
[80] Vegter. J., *et. al* (2003)

For the in situ remediation techniques discussed in this report the treatment duration is moderate-long. Treatment times for chemical and heating methods are in general shorter, than for biological treatment methods, which are dependent on the biological activity in the ground.

A difference to Sweden is that the Dutch remediation policy allows a time frame of 30 years in order to achieve the general remediation goal in order to make cost efficient remediation of plumes possible. However, Dutch experiences of long treatment periods when using biological remediation methods have lead to an increased use of more intensive methods of the source areas often in combination with biological methods to treat the plume areas[81]. This has involved an increased use of new in situ methods in the Netherlands such as chemical oxidation. Examples are the remediation in Oosterhout and Hilversum.

In the Swedish cases commonly applied techniques were groundwater (pump & treat)- and soil vapor extraction. Experiences have shown that adequate source reduction with this method takes very long time[82]. Pump & treat itself has been shown to be very cost-inefficient in some cases if realistic operation periods of sometimes tens of years are considered[83].

5.2.4 Future land use, drivers and goals for the remediation

As discussed in previous chapter, a common problem in Sweden is too often the existing time constraint in the remediation process. Sites with high ecological risks or risks due to high toxicity, concentrations or amount, or risks for spreading often have to be remediated rapidly because of regulatory issues. Other sites may have to wait quite long to be remediated. In case of increased risks on such site due to a change to a more sensitive land use, the priorities are changed. In many cases such sites have to be remediated. The level of clean up is dictated of the future land use.

The problem arises as remediation typically will be considered first when the land is going to be exploited. The planning and time for remediation is often under time pressure, which means great time constraints. In redevelopment projects there is a strong incentive to start building as soon as possible to get back revenues that can pay the investment, including the remediation[84]. Time pressure leads in many cases to poor results and higher costs than in cases with more advanced planning. Remediation will often be considered late in the planning process and the duration of remediation is often underestimated[85].

In the Netherlands non-urgent cases are taken up in the provincial soil remediation program without a defined time for starting the remediation[86]. Therefore spatial development can take into account the quality of a soil at an early stage. In order to enable cost-effective remediation the current Dutch soil policy on soil contamination and remediation also makes it possible for remediation to take several years which encourage parallel redevelopment[87]. In the Netherlands there have therefore been increasing uses of in situ approaches whose

[81] Hoefsloot. P (2007)
[82] Bardos. R. P. *et. al* (2000)
[83] Teutsch. G., *et. al* (2001)
[84] Bergman. J (2007)
[85] Swedish EPA, report 5608 (2006)
[86] Clarinet (2000)
[87] VROM (2006)

operation continue in parallel with site redevelopment and re-use. For mobile contaminants a system has been developed, that determines the cost effectiveness of a measure. Apart from the primary risk assessment, following points are involved when selecting a remediation alternative[88]:

1. Take the time. As natural processes in the soil are slow, the time factor is of vital importance for biological remediation options. Taking the time means attacking a contaminated situation at an early stage. When another application for the soil arises some years later, the location is suitable for that new purpose. Further this implies that in situ degradation process is in progress while the new activities may continue.
2. Use the ’self cleaning capacity’ of the soil. Investigate whether natural degradation processes in the ground are sufficient to obtain acceptable risk reduction over time.
3. Stimulate natural processes
4. Intensive in situ remediation if necessary

The earlier in the process the problem with contamination is considered the better. When the municipalities and the exploiter have knowledge about the pollution and the extent of it, they are also able to assess the costs and duration of a remediation, and whether the redevelopment is viable due to these issues[89].

In some cases, treatment is not immediately necessary, but will be in the future. For example a contamination may not pose a problem under the current land use, but will prevent the site to be sold in the future for other uses. This is a situation where there may be an opportunity to apply long-term treatment solutions to return the site over time to a condition suitable for other uses[90].

5.2.5 Acceptance by stakeholders and trust in the solution

This issue was not deeply surveyed in this investigation. However, it was a constantly recurring issue during the research, which is why it is specially discussed in this chapter. The questionnaire, case studies and interviews revealed a more general picture. A lack in the investigation is that the case studies does not cover cases where conventional techniques where selected instead of innovative techniques. Therefore this report does not describe the whole situation.

According to the questionnaire the acceptance by authorities of the new techniques is a hinder having moderate to high grade of influence to the implementation of innovative technique. Unlike the results in the questionnaire, J. Bergman explains that they seldom experience problems with acceptance to new techniques by the authorities when selecting remedial solution. His experience is that authorities are rather willing and curious about new remediation techniques[91]. That is also a common reaction in the studied Swedish cases. In most cases the authorities where in compliance with the decision and expressed curiosity and optimism about the new technique because it was considered to have less negative environmental impact than for example excavation and transport.

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[88] Clarinet (2002)
[89] Swedish EPA, report 5608 (2006)
[90] Vegter. J., *et al* (2003)
[91] Bergman. J (2007)

In the Netherlands the authorities does normally not take a position in the question of what approach should be used to remediate a polluted site. The authorities only have interest in that the decision is in compliance with the legislation and that the remediation goals are achieved[92]. In Sweden the authorities have the same role. Kjell Färnkvist at the Swedish EPA explains that in projects financed by public means, the authorities should only consider remediation goals and costs. Techniques are evaluated on earlier performance, how they are tested and what uncertainty factors there may be when applying the technique. Because of this reason it is difficult to motivate to try new untested remediation techniques in projects financed by public means[93]. Henrik Ekman at Eco Tec (2007) explains that negative attitude towards innovative remediation techniques normally depend on lack of knowledge and competence. He suggests that one main hinder to the use of new remediation techniques in Sweden is the lack of knowledge and experience in the branch. This implies that nobody is willing to take the risk to spend money on something they don't know give the good results[94].

5.2.6 Research, development and demonstrations

A prominent barrier to new remediation technologies in Sweden is the many uncertainties different stakeholders' experience in respect to implementation. Many techniques that are new to Sweden are already being applied in other countries. Indeed, according to Bardos *et al*, it is common that concerns over feasibility are greater for innovative remediation techniques even these have long standing track records in other countries[95]. This report identifies several uncertainties with respect to implementation of new in situ techniques such as: efficiency of the new technique; the durability of the solution; performance; the results of the remediation operation; the duration of the operation; technical implementation; the costs etc. These uncertainties often lead to the rejection of new in situ techniques.

An important factor leading to the selection of a new technique is, as Johnny Bergman at Soilrem MB Envirotech points out, the importance of being able to offer successful performance information from a few projects before the client is willing to try a new technique. A problem in Sweden is that the contractors can not afford to test the new techniques without financial funding. Another obstacle is that the research money stays in the laboratory and does not follow out in field demonstrations[96].

During the years several research and development programs for innovative technologies have been performed in Sweden. Examples are programs like Soil Remediation in a Cold Climate (Coldrem, http://www.biotek.lu.se/coldrem) and Northern Swedish Soil Remediation Centre (MCN, www.chem.umu.se/mcn).

Swedish EPA has funded some demonstration projects carried out in Sweden. Also the Delegation for Sustainable Technology has funded demonstration projects of different remediation methods. At the moment a research program to stimulate sustainable remediation is ongoing funded by the Swedish EPA. This program is however a knowledge compilation and focus on making existing knowledge about different techniques more available. However, the program does not focus on practical demonstration of remediation techniques[97].

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[92] Veul. M (2007)
[93] Färnkvist. K (2007)
[94] Ekman. H (2007)
[95] Bardos. R.. P (2001)
[96] Bergman. J (2006)
[97] Swedish EPA (2007-05-01)

In the Netherlands a significant amount of means is spent yearly on research and development of new technology. As in Sweden, Dutch stakeholders are in general very optimistic about using new remediation technology, but on the full market it has to be competitive with conventional methods[98]. Therefore the Dutch government facilitates the development and use of new remediation technology by giving money to different organisations working to facilitating the work of soil and groundwater remediation. Efforts in respect of technology development have been focused mainly on optimising existing techniques and developing innovative cheaper alternatives. However, in comparison to Sweden the Netherlands is taking the development one step further; by pilot tests and field demonstrations the use of innovative techniques is stimulated as they are facilitated to become more competitive on the market.

The change in Dutch legislation in 1997 opened up the market for new technologies with less cleanup capacity, than for example traditional thermal treatment. By the enforcement of the new remediation policy, the Dutch government had expectations that in situ techniques could contribute to a reduction of the total cleanup cost of up to 50%. The government realised that new technical breakthroughs were needed to be able to achieve savings on clean up costs. Therefore the government set up a knowledge infrastructure for biological in-situ soil cleaning technologies called NOBIS (Nederlands Onderzoekprogramma Biologish In Situ)[99].

The NOBIS research program was running between 1994 and 1999 with the purpose to support the development of technology implementation. The objective was development and evaluation of innovative strategies, methods and technologies for biological in situ-technologies. The NOBIS program should also support the export of Dutch know-how, products and services. Public as well as private players from the service- and client side have been involved in the program together with representatives from authorities and research and development[100]. In 1999 the NOBIS programme was terminated and replaced by the SKB (Stichting Kennisontwikkeling Kennisoverdracht Bodem). SKB has duration until 2010 and an annual budget of 3.5 million € [101].

However, the Dutch government realised that encouraging research and development would not be sufficient to achieve a fast and cost effective cleanup. There was insufficient overview and guidance of available remediation techniques. The Dutch government recognised that particular to the competent authority it was difficult to appraise remediation techniques which where new to them. Therefore they selected safer solutions that where more certain, which frequently meant high remediation costs. Problem holders also experienced uncertainties including the choice of consultants, the procedures to be followed, and assessment of the gravity of the problem, liability, the environmental conditions and the duration of the remedial operations, the costs and the risks. A more efficient organisation of the cleanup activities was needed and the Dutch government therefore recommended an organisation acting as an intermediary between problem holders, contractors and authorities, and further a knowledge transfer organisation[102]. During the process, apart from SKB, several other knowledge-transfer organisations have been established. More information on different organisations working within the field of soil remediation in the Netherlands is available in appendix 6.

[98] Veul. M (2007)
[99] VROM (1997)
[100] www.skbodem.nl (2006-12-13)
[101] *Ibid*
[102] *Ibid*

5.3 Factors identified by the Swedish remediation branch

The ranking of decision-making criteria is evaluated on basis of the questionnaire. In the first question the participants were asked what influence several different parameters have on the selection of remediation technique. Totally 16 participants answered the questionnaire, but not all answered all the questions. In a next step, the categories were weighted by multiplying the sums of the votes with the following factors: 1 for "negligible", 2 for "low", 3 for "high", and 4 for "very high". Finally these weighted votes are divided by the sum of the answering participants for each parameter (=n) to obtain the ranking order shown in table 10.

Table 10. Ranking-order of decision-making criteria for remediation techniques in Sweden

Parameters	n	Weight
1. Contaminants	16	3.6
2. Technical feasibility	15	3.3
3. Costs	15	3.3
4. Remediation goal/future land use	15	3.3
5. Geological setting	15	3.1
6. Reliability of technique	15	3.0
7. Efficiency	15	2.9
8. Plume- or source remediation	15	2.8
9. Future responsibility	15	2.7
10. Sustainability	15	2.7
11. Available equipment	14	2.7
12. Cost-benefit evaluation	15	2.6
13. Waste management	15	2.5
14. Duration of the remediation	14	2.4
15. Political aspects	14	2.3
16. Requirement of maintenance	15	2.3
17. Available infrastructure	16	2.2
18. Administrative aspects	15	2.0

Besides the expectable parameters of contaminant types, remediation objective and remediation costs, the following parameters seem to be the dominant decision making criteria: technical feasibility, geological setting, reliability of the technique, efficiency and remediation of plume or source.

In question 2 the participants where also asked what factors most often lead to the rejection of innovative remediation techniques. These factors can not be ranked. The most commonly recurring factor are "uncertainties" concerning feasibility, performance, effectivity, results, duration and costs. Other factors are lack of knowledge by the problem holder, "fear" of the unknown, little experience and unproven technique have difficulties to get acceptance by authorities and trust by the problem holder.

Question 5 the participants where asked to indicate the grade of influence of different hinders on the implementation of innovative remediation technology. The votes were ranked in the same procedure as the votes in question 1. The ranking order of the different hinders are given in table 11.

Table 11. Ranking-order of the influence of different hinders on implementation of Innovative remediation technologies in Sweden

Parameters		n	Weight
1.	Trust in involved stakeholders	15	3.5
2.	Ability to offer validated performance information from previous projects	15	3.1
3.	Acceptance by authorities	16	2.9
4.	Ability to verify the effectiveness of the solution when it is applied	15	2.9
5.	Financing	15	2.8
6.	Residual liability	15	2.8
7.	Expertise of the purveyor	15	2.8
8.	Costs	15	2.7
9.	Legislation	15	2.7
10.	Availability of suitable techniques	15	2.3

Hinders with most influence on the implementation of innovative remediation techniques were: trust in involved stakeholders, ability to offer validated performance information from previous projects, acceptance by authorities and ability to verify the effectiveness of the solution when it is applied.

6 Discussion

The aim of this project was to identify differences between Sweden and the Netherlands regarding applied in situ remediation techniques. In general there is a broader palette of in situ techniques being applied in the Netherlands than in Sweden. Several new techniques were identified in the Netherlands, which do not have any known application in Sweden. The aim of this report was further to investigate potential reasons that could explain these differences and identify some of the main opportunities and barriers to innovative in situ techniques in Sweden. Several aspects, important for the suitability of in situ techniques, were investigated and compared between Sweden and the Netherlands. In this report some of the main opportunities and barriers to new in situ techniques were identified. There may still be other important factors than those identified during this project. Some factors do not differ to the Netherlands and are thus not circumstances to why in situ techniques are being less applied in practice in Sweden. Some factors might differ between Sweden and the Netherlands and may influence the use of in situ techniques in Sweden. Finally there are some factors that actually differ from the Netherlands and are more probable to have impact on the use of innovative in situ techniques in Sweden.

Factors that do not differ between Sweden and the Netherlands

There are three main issues to that do not differ to the Netherlands, which are not circumstances why less in situ techniques are applied in Sweden. Apart from the type of contamination, the trigger values, which are applied as measurable remediation goals, do not differ much between Sweden and the Netherlands. The Netherlands as well as in Sweden, applies a risk based remediation policy from which the remediation goals are derived. In the Netherlands it is common to apply the average value ((I+T)/2), which represents a slightly contaminated soil. The results show that when adjusting the Dutch average values with respect to a Swedish standard soil, on which the Swedish generic guideline values are based, they do not differ considerably from the generic guideline values commonly applied in Sweden. Most of the new in situ techniques, presented in this report, have the potential to reduce the risk levels in soil representing the Dutch intervention values. During suitable site-specific circumstances, the techniques have potential to reduce the levels corresponding to the Dutch average value, and in some cases even down to target value. If this was not the case, the techniques would most probably not be applied in the Netherlands. Thus, with respect to the generic guideline values that are commonly applied in Sweden, the new in situ techniques could be suitable to apply in Sweden.

Cost and time are some of the most crucial aspects in the decision making of remediation technique in Sweden according to the questionnaire. However, these aspects are not less important in the Netherlands. Even though the cost is an important criterion when selecting remediation technique in general, it is not considered to be the most significant hinder to implementation of innovative techniques in Sweden. This conclusion is confirmed by interviews with technique providers in Sweden (although not necessarily being representative). Indeed, they also confirm that the prices for applying in situ techniques do not differ much between Sweden and the Netherlands. Thus, the cost itself is not a prominent hinder to application of the new in situ techniques in Sweden.

Interviews with technique providers in Sweden explain that the time aspect is often more crucial than costs, being to a great disadvantage to innovative techniques in Sweden. What is interesting is that the duration of the remediation itself is a parameter placed low in the ranking of decision criteria for selection of remediation techniques. Indeed, the new in situ techniques presented in this report have different duration for remediation, from fast in situ chemical oxidation to slow in situ techniques such as LINER and electro bio reclamation. However, the time constraints that often are related to redevelopment projects is not a unique situation to Sweden. In the Netherlands it is very common that remediation is part of a redevelopment project, with a time schedule to follow. Today there is therefore a trend in the Netherlands of applying faster and high input techniques such as chemical oxidation.

To investigate the suitability of in situ techniques is time costly, and does not often fit in the tight time schedule of redevelopment projects, where remediation often is considered late in the process. A solution to this problem is suggested by the Swedish EPA and the National Board of Housing, Building and Planning in Sweden[103]. To integrate remediation issues in the urban planning process, these issues would get attention at an early stage and there would be more time to make proper investigation and planning. This could therefore be an opportunity to new in situ techniques, which are considered to need more time for investigation and planning. This system is applied in the Netherlands, and implies advantages in terms of planning and performance of remedial operations as it gives more time for slower and more passive in situ techniques. It also opens up the opportunity to plan for remedial operations on a site in parallel to the on going redevelopment works.

Factors that might differ between Sweden and the Netherlands

The Swedish soil environment is in many aspects different to the Dutch. Soil structure and climate are the environmental criteria that differ between Sweden and the Netherlands, and which also might be reasons to why in situ techniques are being applied more in the Netherlands than in Sweden. The permeable and homogeneous soils in the Netherlands is more suitable to apply in situ techniques, than the complex and heterogeneous till, which is the most common soil type in Sweden. However, the geological environment varies between different sites in Sweden and there may be locations that are suitable to apply in situ techniques. Therefore it should not be excluded that the in situ techniques can be applied with success also in Sweden. A detailed analysis on the applicability with respect to environmental criteria was therefore not motivated in this investigation. It would be more relevant to analyse the applicability of a technique separately for each specific site. Therefore the soil texture does not necessarily have to be a hinder to apply the new in situ techniques in Sweden.

The average temperature in Swedish groundwater is approximately the half of the temperature in Dutch groundwater. This affects the biological activity, which slows down, especially at shallow depths. However there are measures to counteract reducing biological activity, such as injection of warm air during the colder seasons. The groundwater temperature tends to stabilise with the increasing depth, where in situ techniques are often applied with advantage to excavation. Some of the new techniques identified in this report are less dependent on the climate, such as chemical oxidation, and heating where heat is produced and even stimulates biological activity. Also electro bio reclamation and electrical bio screens produces heat which stimulates the biological activity. Hence, the colder climate in Sweden does not necessarily have to be a limiting factor to application of the new techniques.

[103] Swedish EPA, The National Board of Housing, Building and Planning (2006)

Cost was according to the questionnaire an important criterion when selecting remedial solution. Interesting is that cost was not considered to be the most significant hinder to implementation of innovative techniques. This can be interpreted as if once it has been decided to remediate a site, the costs for the remediation it self is not most important. Instead it is the cost-efficiency that is important. Cost efficiency can be investigated by comparing costs for different remedial solutions. In Sweden the price for landfill is much cheaper than in the Netherlands, which makes it a more cost efficient alternative in Sweden than in the Netherlands. Thus, the low landfill fee leads to less economic incentive to apply in situ techniques. On the other hand, the ex site treatment techniques are cheaper in the Netherlands than in Sweden. This might in some cases be a reason in the Netherlands to select excavation and treatment off site, for example for remediation of hot spots in the unsaturated zone. One opportunity to increase the interest of in situ techniques in Sweden would be to introduce a higher environmental tax on land filling, such as in the Netherlands. This is probably the most effective way to make in situ remediation more interesting alternative in terms of cost-efficiency. Especially if the reduced transport costs, that is one of the benefits of in situ remediation, are taken into consideration. However, important aspects that have influence on why contaminated soil is not often placed on landfills in the Netherlands is the strict policy on land filling that is applied. Land filling is strictly seen as an “end of pipe” solution which means that only soil that can not be treated or is proven to be too expensive to treat can be placed in a landfill. A special declaration is needed for such cases and is provided by the organisation Bodem+.

Factors that differ between Sweden and the Netherlands

One important difference in between Sweden and the Netherlands is the applied overall strategy of the remediation. In the Netherlands several different approaches are applied due to the differentiation of the pollution. An integrated or combined remediation approach is often a more efficient way to achieve the environmental goals, in situations with differentiated pollution, than using one single technique. In the Netherlands different techniques are combined for remediation of for example hot spot, source and plume areas. Excavation of hot spots in combination with in situ for source areas and plumes is one example. Also combinations of active and passive techniques, long- and short-term techniques and long-term monitoring are common in the Netherlands. In Sweden on the other hand different techniques are mainly integrated when the pollution is differentiated in the saturated and unsaturated zone. Special treatment of free phase contamination is not as common in Sweden as in the Netherlands. The main reason to these differences is the remediation policy that is practised in the Netherlands, which for mobile pollution situations is strongly focused on preventing further spreading of the pollution. Monitoring is therefore a crucial part of the remediation work in the Netherlands. The aim is often stable and environmentally acceptable end-state. Thus some residual contamination is allowed as long as it is not growing or moving. In order to be able to remediate cost efficient, plume remediation are allowed to take up to 30 years, which gives the opportunity to apply more extensive in situ techniques.

In Sweden on the other hand, there is no such specified guidance and no established custom on how to handle different pollution situations. It is in each case the authority’s task to decide whether the remedial solutions can be accepted or not and the requirements of monitoring program after the remediation. The lack of knowledge and experience makes it difficult for the authorities to make an appraisal of suggested solutions where new in situ techniques are suggested. The lack of knowledge and understanding of the application of the risk based guideline values may have a negative effect on the use of in situ techniques as unreasonable remediation goals are drawn up. As a result, the remediation goals often have to be reassessed which prolongs the remediation process and make it even more costly. This may contribute to the augmentation of perceived insecurity of new in situ techniques. Perhaps a more detailed guidance on different pollution situations would open up the opportunities in Sweden for applications of for example the source and plume approach that are often being applied in the Netherlands. On the other hand, it is important not to forget that the guidance inclusive the generic guideline values available in Sweden is only guidance and recommendations. They are not directions or general advice, as the policy in the Netherlands. This implies a great flexibility in the Swedish system, and allowance in the authority appraisals. This flexibility could also mean an opportunity to new in situ techniques.

However, long term monitoring programs are being avoided as far as possible in public funded remediation projects in Sweden. The reason is the difficulty to guarantee funding as public grants are political governed and are only given for one year at a time. This is limiting factor to the application of long term in situ techniques in public funded projects.

Another explanation to the previously discussed differences in applied overall strategy could also be the expertise of the many different contractors that are available in the Netherlands. Today the government leaves more often the problem to the technique provider, who contacts a consult agency to plan the remediation. In this way there is a greater involvement by the contractor, who has the expertise of the techniques. In many cases one contractor can also apply several different techniques together.

The last but not least important difference between Sweden and the Netherlands is the experience of applying different in situ techniques. In contrast to the Netherlands there are limited experiences of performed in situ techniques in Sweden. This can partly be explained by the limited number of remedial operations that in total take place in Sweden each year. In average there have been ten times as many remediation projects carried out in the Netherlands than in Sweden, which means more opportunities to apply in situ techniques and hence more opportunities to gain experiences from application in practice. The limited experience can also be explained by the short period of time that Sweden has experience of soil and groundwater in comparison to the Netherlands. One reason to why the Netherlands more often apply in situ techniques is of course the compact densely build up city environments, due to the high density of population, which give less space for excavation.

The limited experience gives rise to many uncertainties experienced by the Swedish remediation branch. These experienced uncertainties are indeed circumstances to why problem holders are afraid of trying the new techniques. Even though several of the new techniques are being applied in other countries, there are concerns over their feasibility in Sweden. Negative attitude and carefulness arise mainly from lack of knowledge and limited experience.

However, the lack of experience is not an acceptable excuse to why new “untested” techniques are not being applied in Sweden. Several of the techniques that are applied in the Netherlands are developed in other countries, such as North America. This shows that also the Dutch remediation branch use knowledge and expertise developed in other countries in order to proceed in the cleaning up of polluted sites. The governmental organisation SKB has played a crucial role in the transfer of knowledge and expertise into the Dutch remediation branch.

In the questionnaire, availability of suitable techniques is given the lowest rank of suggested hinders to implementation of innovative techniques in Sweden. Indeed, information about most techniques is found in literature, often available on the Internet, which today is the main source of information of state-of-the-art remediation technology. With the Internet and international exhibitions- and conferences on remediation technology, information of innovative techniques becomes available to anyone, who is interested, if only one knows what to look for.

As in the Netherlands, the Swedish government has funded research and development through different programs. However, these efforts are not enough to facilitate the implementation of new techniques. In order to facilitate and stimulate the implementation of new in situ techniques in practice future efforts must be focused on actions, which give more trust in the implementation of new techniques. More information is needed to reassure the remediation market that innovative technology is viable. The best and most important way is to give demonstrations of different new techniques in Swedish environments. Such demonstrations would lead to increased knowledge and more experiences of the implementation in practice in Swedish environments, and hence reduce the insecurities experienced among Swedish stakeholders. Today the Swedish government is funding remediation of the largest and most serious cases, in which they do not allow the application of new “untested” techniques. In parallel to remediation of the large cases the Swedish government should support demonstration programs of smaller sites. In this way the new techniques would be tested in Swedish environments.

However, the efforts described above are little worth if they are not properly coordinated and made available to the end users through an efficient organisation. Today the Swedish EPA and the Swedish clean soil network (www.renaremark.se) provide a platform of development and guidance on different aspects related to soil remediation. These platforms should be better coordinated and expand to also comprise information on different demonstration projects, risk policy, decision making and state of the art remediation technology provided by different contractors. The latter is crucial as a first step to introduce innovative technologies and make them more familiars to the Swedish remediation branch. It is important that such a platform serve as an intermediare between different stakeholders in the remediation branch, so that one can make the best use of the gathered knowledge and experiences. Guidance on state of the art in situ technology could also become more available through handbooks in Swedish intended to problem holders, technical advisors and authorities. Such handbooks should also comprise important aspects on risk policy, decision making and the implementation of remediation technologies. In order to create a living handbook, it is important that they are up-dated regularly on basis of new experiences gained from implementation in practice.

In general there seem to be a curiosity and optimism among problem holders towards new remediation techniques. This is the greatest surprise from and probably also the greatest opportunity for an increased use of the new in situ techniques in Sweden in the future. Many persons associate new techniques with benefits such time-and cost reductions and less negative environmental impact due to less transports, better use of nature resources and a smaller operation on site.

Finally, it is the Swedish government and the environmental protection agency that have the most decisive role to influence at what extent new in situ techniques are applied in Sweden. The Swedish EPAs main tasks are to co-ordinate and promote environmental work towards a sustainable development at a national and international level. In order to make remediation activity itself more sustainable, they must take actions, which facilitate the implementation of more environmental sustainable remediation solutions.

7 Conclusive remarks

Techniques applied in the Netherlands with no previous known application in Sweden are Co-solvent/surfactant flushing, LINER, six-phase heating, electro bio reclamation, electro kinetic bioscreens and in situ chemical oxidation with C-sparge and Perozone.

None of the new techniques can be excluded to be suitable to apply in Sweden with respect to environmental criteria, since the environment is unique on every different site. The opportunities for success of each technique must be investigated for each specific site.

A common opinion in Sweden is that the Netherlands uses new soil remediation technologies and therefore are leading in the field. However this hypothesis was partly denied as most of the innovative techniques used in the Netherlands are already known in Sweden, but not applied in practice.

Factors that are the same between Sweden and the Netherlands and thus not circumstances to why less in situ techniques are applied in Sweden are the type of contamination, the applied remediation goals and cost and time aspects.

Factors that might differ between Sweden and the Netherlands are the soil structure, climate and the cost compared to other techniques.

Factors that do differ between Sweden and the Netherlands are the involvement of contractors in making the remediation plan, the overall strategy and remediation policy, and the expedience and guidance of performing different in situ techniques.

Demonstrations of new in situ techniques in Swedish environments may be the best and most important opportunity to facilitate and stimulate implementation of new in situ techniques in practice.

This report was giving an overview of the innovative techniques applied in the Netherlands. Therefore it would be interesting to investigate the applicability in Swedish environments by means of laboratory studies following with field applications. However, this report further identifies several factors, other than environmental, which may have influence on the use of innovative in situ techniques in Sweden. Therefore, further studies should not only be focused on the applicability of the techniques themselves, but also to investigate and formulate practical suggestions on how to stimulate the use of the innovative remediation techniques in Sweden.

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Definitions

Abiotic	Nonbiological processes: also used to refer to nonbiological degradation process
Advection	The process of transfer of fluids (vapors or liquid) through a geologic formation in response to a pressure gradient that may be caused by changes in barometric pressure, water levels, wind fluctuations, or infiltration
Aerobic	Condition in which oxygen is present: also used to refer to a type of microbe that requires oxygen to live and reproduce
Bench-scale	The bench-scale is that stage of development at which an IT has been shown to be feasible using laboratory equipment but for which insufficient data are available to attempt to test or implement the technology at full-scale
Cesspool	A dry well for the disposal of sewage
Confining layer	Impermeable layer (such as clay) that impedes the vertical migration of groundwater or NAPL
Diffusion	The movement of suspended or dissolved particles (or molecules) from an area of higher concentration to one in which concentrations are lower. This process ends to distribute the particles or molecules more uniformly
Dispersion	The process by which a substance or chemical spreads and dilutes in flowing groundwater or soil gas
Electron acceptor	A compound capable of accepting electrons during oxidation-reduction reactions. Electron acceptors are compounds that are reduced during the process and include oxygen; nitrate; iron (III); manganese (IV); sulphate; carbon dioxide; or, in some cases, chlorinated aliphatic hydrocarbons, such as carbon tetrachloride, PCE, TCE, DCE, and VC
Electron donor	A compound capable of supplying (giving up) electrons during oxidation-reduction reactions. Electron donors are compounds that are oxidized during the process and include fuel hydrocarbons and native organic carbon
Full-scale implementation	The full-scale implementation stage is that stage of development at which an IT has been tested and proven feasible for use at specific sites, but still lacks cost and performance data adequate to facilitate the use of the technology on a large-scale, commercial basis

Full-scale testing and demonstration	The full-scale testing is that stage of development at which an IT is tested outside the laboratory and in a manner that demonstrates the technology's potential usefulness in the implementation of large-scale cleanups
Function-oriented cleanup	Required soil quality of a particular site depends on its future use
Implementation	The process of applying a remedial approach to a particular site
Innovative technologies	Newly developed technologies that lack sufficient full-scale application data to ensure their routine consideration for site remediation
In-situ remediation	A treatment process where excavation or other removal of the contaminated material(s) does not take place
Integrated remediation	Both soil and groundwater are remediated
mg/kg d.s	Milligrams of the contaminant per kilogram of dry substance soil
Multifunctional cleanup	Soil is completely clean and every type of soil use is possible after cleanup. No supplementary management or after-care is needed
Phased remediation	
Pilot-scale	The pilot-scale is that stage of development at which sufficient data have been obtained about an IT to demonstrate that the technology may be feasible at full –scale and for which sufficient data are available to establish the design and operating conditions needed to test the IT at full-scale
Plume area	Area in the ground where contamination is dissolved and spread with the groundwater
Remediation	Removal of pollution or contaminants from environmental media such as soil, groundwater, sediment, or surface water for the general protection of human health and the environment or from a brownfield site intended for redevelopment
Source area	Area in the ground where free phase contamination is encountered
Sub soil	Soil deeper than approximately 1,5 meters
Till	Till is an unsorted glacial sediment. Glacial drift is a general term for the coarsely graded and extremely heterogeneous sediments of glacial origin. Glacial till is that part of glacial drift, which was deposited directly by the glacier.
Top soil	Soil down to approximately 1,5 meters

List of acronyms

CAH	Chlorinated aliphatic hydrocarbons
CF	Chloroform
CT	Carbon tetrachloride
DCA	Dichloroethane
DCE	Dichloroethene
DNAPL	Dense Non Aqueous Phase Liquid
ISCO	In Situ Chemical Oxidation
MC	Methylene Chloride
NAPL	Non Aqueous Phase Liquid
PCE	Perchloroethylen
TCE	Trichloroethene
VC	Vinyl Chloride
VOCl	Volatile Chlorinated Hydrocarbons

Appendix

List of content:

1. Applied in situ techniques
2. Description of innovative in situ remediation techniques
3. Overview in situ techniques
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5. Case studies
6. Dutch organisations in soil remediation

Appendix 1/ Applied in situ techniques

Experience / In situ techniques	Experience The Netherlands[104]	Status The Netherlands[105]	Experience Sweden[106]
Extraction techniques			
Groundwater extraction/ pump and treat	Widely spread	1	Widely spread, full-scale
Groundwater recirculation wells	Field-scale application	3	No information
Surfactant/ C-solvent flushing	Few	3	No application known
Dual phase/ multiphase vacuum extraction (bioslurping)	Many tens of cases	2	Pilot-scale, full-scale[*]
Phase separation fluid pump	Field-scale	3	Not applied
Air sparging/ bio sparging	Widely spread, full-scale	1	Widely spread, full-scale
Soil vapor extraction	Field-scale	1	Widely spread, full-scale
Steam enhanced extraction	Field-scale application	3	Few
Electro reclamation	Proven	3	Not applied
EBR (electro bio reclamation)	Widely spread	3	Not applied
Degradation techniques			
Aerobic biological degradation			
Monitored natural attenuation (MNA)	Full-scale	2	2 pilot-scale

[104] SKB, 2007-04-03
[105] SKB, 2007-04-02
[106] Statens naturvårdsverk, 2007
[*] Däldehög Miljö AB, 2007-05-18

Enhanced aerobic biological degradation	Full-scale	1	Full-scale
Anaerobic biological degradation			
Enhanced anaerobic biological degradation	Full-scale	1	No full-scale application known
Liner®	Full-scale	3	Not applied
Chemical reduction			
Zero valent iron barrier	1 field-scale project	3	1 full-scale demonstration
Chemical oxidation			
KEMOX	Not applied		1 full-scale project
Fenton's reagent	Proven	2	Field-scale test*
C-sparge™	Proven	3	Not applied
Perozone™	Proven	3	Not applied
Heating			
Six-phase heating	Field-scale, full-scale	3	Not applied
EBIS (electro kinetic bio screens)	1 project	3	Not applied

1= Commercial available, applied on a regular basis
2= Commercial available, moderately applied
3= Commercial available, limited applied in the field
4= Not implemented in the field

* Däldehög Miljö AB (2007-05-18)

Appendix 2 / Description of innovative in-situ remediation techniques

Description of techniques

Following chapter is a brief description of the techniques available in the Netherlands but not commonly applied in Sweden. Information about the techniques has mainly been gathered from the SKB website and the websites of the different contractors linked from the SKB website. For information of the other techniques more commonly applied in Sweden and the Netherlands, the reader is referred to information available at the Swedish EPA.

Liner®[107]

A normal problem when injecting solution into the ground is clogging of filter. In order to avoid that problem, this technique has been developed. The liner technique involves the injection of substrate into the soil to stimulate anaerobic dechlorination of anaerobic degradable contaminants such as aliphatic hydrocarbons (CAH). The substrate is nebulized in a nitrogen carrier gas. By using nitrogen gas the oxygen is driven out the soil and the soil becomes or stays anaerobic. This method combines two concepts: stimulation of biodegradation of CAHs by the addition of an electrondonor substrate, and in-situ air sparging. The flow rate at which gas is distributed both horizontally and vertically within the soil is expected to be much higher than that of water, which makes the injection of gas a much more effective than infiltration of an aqueous solution. By introducing substrate with a carrier gas the mixing of the substrate with the groundwater is better than introducing the substrate as a solution. Also the costs of injecting gas at great depths are relatively low in contrast to for example groundwater infiltration. The technique is suitable to apply for deeper soil- and groundwater contamination in source- as well as plume areas.

Co-solvent Flushing

Co-solvent flushing can be applied as a stand-alone technology or as a component in a treatment train to enable application of following techniques. The principle of this technology is to increase the water solubility of poorly soluble contaminants by injection of a mix of water and additives such as surfactants or co-solvents via filters in the soil. By increasing the water solubility of the contaminants the removal of the contaminants from the soil is easier and the mobilised contaminant. The co-solvent mixture is normally injected up-gradient of the contaminated area, and the solvent with dissolved contaminants is sweaped and extracted in a system of wells down-gradient and treated above ground. The technology is applied to increase the solubility of contaminants such as oil, diesel and PAHs and is mainly used for source contamination in the saturated zone. This technique requires moderate to high good permeable soils. Peat soils are not suitable. Factors that limit the applicability may be permitting concerns due to introduction of surfactants and solvents to the subsurface.

Phase separation fluid pump

The technology is applied to remove free phase floating product from a well drilled for remediation purposes. During the process two pumps are used; one to remove floating product and the other to remove water beneath the floating product. The technology is suitable to apply for organic non-chlorinated contaminants in the saturated zone of the source and the high-end plume. The removed product is properly disposed and the separated water is treated. The technology must be used in combination with other techniques to complete the

[107] www.tauw.nl (2007-04-05)

remediation. The technique is often combined with air sparging, air injection or steam injection. A precondition for application is that there must be a constant concentration high enough to make the technique cost efficient[108].

In Situ Chemical Oxidation (ISCO)
In situ chemical oxidation is suitable to treat groundwater contaminated with saturated and unsaturated hydrocarbons, (chlorinated) alkanes, ethers, alcohols, (chlorinated) alkenes, free cyanide, mono- and polycyclic aromatics[109]. The oxidator is produced in the right concentrations in a special unit and is normally injected in the soil by the use of filters. In a remediation project in Sweden the oxidant was mixed in the soil volume as granule crystal (see case study Petrol station in Bottnaryd page). When the contact time between the organic contaminants is sufficient, chemical oxidants may be capable of converting the petroleum hydrocarbon mass to carbon dioxide and water. Due to the exoterm reaction there will be an increase in temperature and pressure in the groundwater, which may lead to movements in the groundwater, stimulating the biological degradation. Due to the increased pressure, the spreading of the oxidant in the groundwater is improved.

Chemical oxidation technologies are commonly applied to remediate contaminants in the saturated zone in the source area. ISCO requires high permeable homogenous soils with low organic matter content, as the chemical oxidant may not be able to penetrate low permeability homogenous soils or horizons in heterogeneous soils. The presence of organic material in the soil may cause extensive loss of oxidant that is reacting with organics in stead of reacting with the contaminant. Also the Elevated levels of dissolved mineral species such as ferrous iron (Fe^{2+}) may affect the ability of the oxidant to reduce the target contaminant. Oxidising reactions with the dissolved iron consumes the oxidant aimed for destroying the target contaminant. Solid precipitates are produced that can accumulate in the soil pore spaces, which on a large scale could reduce effective soil porosity[110]. Chemical oxidation technologies also rely on groundwater advection and dispersion to distribute oxidants and catalysts reagents in the subsurface. The technologies are therefore dependent on a horizontal groundwater flow, which can be either occur naturally or being stimulated by extraction wells. Chemical oxidation, mainly permanganate, has been tested for treatment of contaminated groundwater in fractured bedrock with positive results[111]. es of chemical oxidation in contrast to other remedial technologies is the rapid destruction or degradation of contaminants (measurable in weeks or months). Disadvantages are the requirement of special precautions due to the production of explosive off-gas involved in the application of some oxidants. Significant health and safety concerns are associated with applying oxidants.

The most commonly applied oxidants in the Netherlands are Hydrogen Peroxide/Fenton's Reagent, Ozone, Perozone and Potassium or Sodium Permanganate. In Bottnaryd the chemical oxidation technique KEMOX[112] was applied.

Hydrogen Peroxide and Fenton's Reagent

[108] SKB, 2007-04-04
[109] SKB, 2007-04-04
[110] Chemical oxidation www.epa.gov, 2007-04-04,
[111] Stone P.R., and others, 2000
[112] http://www.detox.se

Hydrogen peroxide (H_2O_2) is a strong oxidant injected in the contaminated zone to destroy petroleum products. Peroxide is typically transported to the remediation site in liquid form at high dose concentrations. When injected to groundwater peroxide reacts with organic contaminants and subsurface materials. During the reaction oxygen and water is produced within hours of its introduction into the groundwater, generating heat. Hydrogen peroxide is particularly effective in contact with ferrous iron (Fe^{2+}). Iron work hereby as a catalyst and occurs naturally in the soils or may be added as a solution together with the hydrogen peroxide. Hydrogen peroxide reacts with ferrous iron to form hydroxyl radicals (OH•), ferric iron (Fe^{3+}), and hydroxyl ions (OH^-). The hydroxyl ions are very strong oxidizers and react typically with organic compounds. The hydroxyl radicals break down petroleum products such as benzene, toluene, ethylbenzene, and xylene, as well as petroleum aromatic hydrocarbon (PAHs) and methyl tertiary butyl ether (MTBE). Hydroxyl radical is such a strong oxidant that the reaction with organic compounds proceeds so quickly, that the contact time between radicals and contaminant molecules is not sufficient to destroy the contaminants before the radical decomposes. Some contaminants sorb very tightly to organic material in the soil and are not easy available of destruction. Other disadvantage of Fenton's reagent is the migration of explosive vapors that the reaction generates. Handling of peroxide is also associated with a lot of health risk and requires special safety precautions. A positive effect of applying peroxide and Fenton's Reagent is the enhanced aerobic degradation due to the increase of oxygen levels in and around the treatment area. Also reduced nitrogen and sulfur are oxidized to nitrate and sulfate, which can be used as nutrients by microbes[113].

Ozone (C-sparge™)

Ozone is a strong oxidant and can be used sparge wells need to be places closely in the target zone of remediation. Ozone injected into the groundwater can oxidize contaminants directly or through the formation of hydroxyl radicals (OH•). Special micro porous filters are used for the injection of ozone, creating bubbles coated by a reactive layer of ozone. Ozone is capable of oxidizing petroleum contaminants such as chlorinated hydrocarbons, BTEX, PAHs and MTBE, with some special considerations[114] of such as unwanted intermediary products and cost-effectiveness. Chemical oxidation is effective on high carbon concentrations typically found in groundwater and soils in source areas, and may not be effectively applicable to lower concentrations in plumes. For a highly soluble compound like MTBE typically found in laterally extensive and mobile groundwater plumes, the cost-effectiveness should be considered before using chemical oxidation. The primary benefit of in situ decomposition of ozone is the oxygenation and bio stimulation it generates, as the unstable ozone decomposes to oxygen molecules. The injection system of ozone can be equipped with a pump, enabling recirculation of groundwater through the filters[115]. For more information about groundwater circulation wells see 4.2.1.to destroy petroleum hydrocarbons in-situ. Most commonly ozone gas is injected or sparged directly into contaminated groundwater. Due to ozone's high reactivity and instability, ozone must be generated on site in close proximity to the treatment area, and

Perozone™

Perozone™ is an optimization of chemical oxidation in the means of ozone. The improvement lays in the combination of ozone and hydrogen peroxide, generating an oxidation potential in the magnitude of Fenton's reagent. As the air/ozone is injected in the ground it passes a micro filter with dissolved hydrogen peroxide, leading to the formation of micro bubbles of air and ozone. Due to this improvement, intensification in the production of ozone-coated bubbles is

113 Chemical oxidation www.epa.gov, 2007-04-04
114 Chemical oxidation www.epa.gov, 2007-04-04
115 Tauw, 2006

possible, which makes the technique more efficient during application in the contamination source zones. The first remediation with Perozone in the Netherlands was performed in the end of 2003[116].

Heating

Steam enhanced extraction

Steam enhanced extraction is a process which is applied to remove volatile and semi-volatile contaminants from the subsurface by heating the soil with injected steam to volatilise them, while forcing mobile liquids in from of the moving steam zone[117]. Introduction of heat to the subsurface speeds up mobilisation processes and the diffusion for the liquid-, soil gas-, and solid phase of the NAPL[118]. The most important processes speeding up the mobilisation is volatilisation and desorption of contaminants from the soil structure to dissolve and evaporize[119]. Liquids displaced by the injected steam are pumped from extraction wells. Vapors containing volatilised contaminants are captures by vacuum extraction. Extracted groundwater and vapors are cooled down and condensed. In addition to physical removement the injected heat enhances biological and chemical processes[120]. Steam enhanced extraction is an extraction method which suitability primary is dependent on the properties of the contaminants and the permeability of the soil. Therefore clay- and silty soils are not appropriate for this technique. Steam enhanced extraction can be applied in the saturated as well as unsaturated zone, which makes this technique suitable to use at great depth[121]. The technology has also been tested for fractured bedrock[122].

Six-phase heating™

Six-heating is a technology where contaminated soil and groundwater are resistively heated at a temperature high enough to vaporize contaminants. Heat is generated by low frequency electricity flowing into the ground through electrodes, which are drilled into the ground and arranged in a hexagonal pattern over the contaminated area. The vaporized contaminants are collected and treated. The technique is suitable to apply in the saturated as well as unsaturated zone for source contamination, especially DNAPL and LNAPL products can be treated well[123]. The technology works particularly well in heterogeneous and impermeable soils that are normally difficult to remove contaminants from. The technique can be applied to soils contaminated with volatile contaminants such as chlorinated solvents and BTEX. Also oil products can be remediated. Requirement for the technique to work efficiently is good conductivity in the ground with soil moisture of minimum 10%[124].

Electro-bio reclamation (EBR)[125]

Electro bio reclamation increases the efficiency of techniques like air sparging, bio sparging and bio degradation by increasing the soil temperature with radio frequency heating by

[116] Tauw, 2006
[117] US EPA, 2005
[118] Tauw, 2006
[119] Tauw,2006
[120] US EPA, 2005
[121] Tauw, 2006
[122] US EPA 2005
[123] SKB, 2007-04-04
[124] Tauw, 2006
[125] Holland milieutechniek (2007-04-10)

applying electromagnetic energy in the means of alternating current. The increase of the soil temperature enhances a number of physical and chemical processes such as:

- Decrease of the specific mass of the heated groundwater and the dissolved components therein.
- Increase of the solubility of the contaminants
- Increase of the rate of solubility of the contaminants
- Increase of the vapor pressure of the different solution mixtures
- Increase in permeability for water as well as hydrocarbons in tight soils
- Increasing effect on microbial activity in the soil. By injecting nutrients into the ground, biodegradation of organic pollutants is further enhanced.

The in situ technique is applied to clean up soil and groundwater contaminated with BTEX aromatics, chlorinated hydrocarbons (DNAPL), diesel and fuel oil, light PAH and phenol. The technology is primarily applicable to pollution source areas with high concentrations and/or free product, as areas with lower concentrations can be remediated at a later stage. Temperature increase is faster and most easily achieved in the saturated zone where the transition resistance is lowest. The rising heat from the saturated zone will also heat up the overlaying layers in the unsaturated zone. The technology can be applied to clay, sand and peat soils.

Inserting electrodes into the ground in a fixed pattern creates heat in the soil. The electrodes are in general placed at the lowest point of the groundwater contamination. Extraction filters and injection points for compressed air and nutrients are installed between the electrodes according to a specific pattern. Purification equipment for groundwater and soil vapors as well as the energy supply is housed in containers.

In addition, the technology can be applied in the form of an electro kinetic (bio) fence, so called electro biological screens, as a passive in-situ cleanup method for containment and remediation of contaminated groundwater plumes.

Electro Biological Screens (EBIS)[126]

The remediation technology is based on transport processes that occur if an electric field is applied to a soil. A screen of electrodes is placed down stream the contamination plume. Upstream the electrode screen filters are placed to inject nutrients for the stimulation of biological activity. The contamination will be transported towards the electrode screen by the groundwater flow. As the contaminants reaches the zone of influence of the screen of electrodes, electrically charged contaminants will be transported to either the anode or the cathode and removed from the soil by a special filter filled with a continuous conditioned liquid. Nutrients such as nitrogen, phosphorus, oxygen donors, organic compounds, spore elements etc. necessary for biodegradation of organic pollutants dissolved in water, appear almost always as electrically charged compounds and can be dispersed through the soil electro kinetically. Addition of nutrients in combination with the increased temperature in the ground enhances the biological degradation of organic contaminants in the ground.

The electro biological fence is set up as a row of electrodes bordering a hotspot or groundwater plume, perpendicular to the groundwater flow direction and installed to the lowest point where pollutants are found. When EBIS is applied, alternating current is applied, creating a zone where temperature is raised and biological activity is stimulated. A row of

[126] Holland milieutechnik

filters for nutrient infiltration is installed upstream from the electrodes. Direct current is applied and will homogeneously disperse electrically charged nutrients by the groundwater electro kinetically. Electro-kinetic (bio) fences can be installed at relatively great depths and over great distances, avoiding extraction of large volumes of groundwater.

EBIS is a passive in situ method to screen off and control source areas as well as control and remediate groundwater plumes contaminated with either or both inorganic and organic pollutants. The technology is applicable to diffusely dispersed pollutants in clay, sand and peat soils.

Passive in- situ method to fence off and control source areas as well as to control and remediate groundwater plumes contaminated with either or both inorganic and organic pollutants. The technology is applicable to diffusely dispersed pollutants in clay, sand, and peat soil.

	Contaminants	**Climate**	**Application area**		**Phase distribution**			**Geological conditions**						**Geo-chemical conditions**
Technology			Source	Plume	Saturated zone	Un-saturated zone	Free product phase	Sand / gravel	Clay / silt	Fractured bedrock	Heterogeneous soil	Layered soils	Organic content	pH
Surfactant/ Co-solvent flushing	Oil, diesel, PAH	-	X	~	X	X	X	X	No	~	~	-	No	Not specified
Fenton's reagent	Saturated and unsaturated hydrocarbons, chlorinated solvents, cyanide, PAH	-	X	X	X	X	No	X	X	X	~	No	No	Low
C-sparge™	Saturated and unsaturated hydrocarbons, chlorinated solvents, cyanide, PAH	-	X	X	X	X	No	X	X	X	~	~	No	Low
Perozone™	Saturated and unsaturated hydrocarbons, chlorinated solvents, cyanide, PAH	-	X	X	X	X	No	X	X	No	~	~	No	Low
Six-phase heating	Volatiles, chlorinated solvents, BTEX, Oil products	No limitations	X	X	X	X	No	X	X	-	X	X	X	No limitation
EBIS	Charged biodegradable contaminants	No limitations	~	X	X	No	X	X	X	No	X	X	X	Normal
EBR	Volatile inorganic, volatile organic, hydrocarbons and mineral oil	No limitations	X	X	X	X	X	X	X	No	X	X	X	Conductivity, Normal
LINER® (Liquid Nitrogen Enhanced Remediation)	Anaerobic degradable contaminants	-	X	X	X	X	No	X	No	No	~	~	No	Normal
Phase separation fluid pump	Organic non-chlorinated contaminants	-	X	X	X	No	X	X	~	No	~	~	-	No limitation

X = applicable for given conditions
~ = application less suitable for given conditions or limited experience
No = not applicable
- = Information not found

Appendix 3 – Overview in situ techniques

Technology	Residual concentrations	Time span Remediation	Relative cost (€/m3)
Surfactant/ Co-solvent flushing	Depending on soil and contamination	<0,5 year	-
Fentons reagent (No info)	Site specific		
C-sparge™	Site specific	1 month -2 years	Plume 2-20 Source 20-40
Perozone™	Site specific	1 month -2 years	Plume 2-20 Source 20-40
Six-phase heating	Target values	3-4 months	20-120
EBIS	<average value	1-3 years	50-150
EBR	Target values	0,5-10 years, site specific	Source 50-150 Plume 0,1-10
Liner®	Site specific	Soil contamination 5-10 Groundwater contamination 1-5	-
Phase separation Fluid pump	Not used to completely clean up site Used as a first step towards remediation	>1 year	-

Appendix 4 / Properties of petroleum hydrocarbons and chlorinated solvents

When selecting a suitable remediation it is important to consider the behavior of the actual contaminant in the ground due to its physical and chemical properties. This section aims at describing the most important properties and different transport processes in soil and groundwater to take into consideration when selecting an adequate remediation solution for soil and groundwater contaminated with petroleum hydrocarbons or chlorinated solvents.

Petroleum hydrocarbons

Usage and sources

Petroleum hydrocarbons are the hydrogen-carbon containing compounds originating from crude oil. Petroleum is mostly used, by volume, for producing fuel oil and gasoline. Other area of usage is as raw material for many chemical products including solvents, fertilisers, pesticides, and plastics.

Physical and chemical properties

Petroleum products extracted from crude oil includes gasoline, diesel, jet fuel, and water-soluble components of gasoline and fuel oil[127]. There are several hundred individual hydrocarbon chemicals defined as petroleum-based. Crude oil varies in its compositions and some of its variations are reflected in the petroleum product. Therefore each petroleum product has its own mix of constituents. Some products contain a defined range of components with specific fractions such as jet fuels. Others for example automobile gasoline contain a broader range of hydrocarbon types and amounts[128].

Petroleum hydrocarbons can be divided mainly into aliphatic and aromatic hydrocarbons.

- *Aromatic hydrocarbons* have one or more benzene rings as part of their structure. Monoaromatics are aromatics with one benzene ring as part of their structure and polycyclic aromatic hydrocarbons (PAHs) are aromatics with two or more fused benzene rings. Monoaromatics, such as benzene, toluene, ethylbenzene, and xylenes (BTEX), are some of the most common aromatic compounds in petroleum[129].

- *Aliphaticc hydrocarbons* are hydrocarbons, which consists of alkanes and alkenes.
  - *Alkanes* are saturated hydrocarbons containing only single bonds between the carbon atoms. Alkanes can also have a cyclic structure and are then called cycloalkanes.
  - *Alkenes* are unsaturated hydrocarbons and contain one or more double bonds between the carbon atoms.

Solubility is an important property affecting the contamination migration in soils, groundwater, and surface water. Solubility is expressed in terms of the number of milligrams of a constituent that can be dissolved in 1 l of water (mg/l) under standard conditions of 25°C and one atmosphere of pressure (atm). The higher the value of solubility Petroleum hydrocarbons is distinguished by a decreasing solubility and volatility as the number of carbon atoms increases. The ability to adsorb to organic material increases with increasing

[127] Heath *et al.* , 1993
[128] ATSDR Toxic Profile
[129] Fate and Transport of Petroleum Hydrocarbons in Soil and Groundwater at Big South Fork National River and Recreation Area, Tennessee and Kentucky, 2002-2003.

number of carbon atoms. Aromatic hydrocarbons, especially BTEX, tend to be the most water-soluble fraction of petroleum hydrocarbons and are considered to be VOCs[130]. BTEX also have the lowest soil organic carbon sorption coefficient (K_{oc}) of the most common aromatic hydrocarbons. Benzene, toluene and xylene are considered to be high to moderate mobile in soil[131]., the greater the tendency of a constituent to dissolve in water. For organic constituents, solubility depends on the form of constituents. Volatility is another important property affecting the mobility and persistence of organic consistuents and several forms of inorganics. Henry's law constant is an indication of the tendency of a constituent to volatize from the aqueous or water phase to the vapor phase and is dependent of the vapor pressure and solubility of the constituent. The potential for a constituent to adsorb to soil and sediment particles effects the migration through soil and aquifer materials as well as migration from surface water and sediments.

Mineral oil

Mineral oil is not a group of compound, but an umbrella term based on a special analysis method, most common gas chromatography. Compounds as benzene, diesel, and heating oil are complex mixes of aromatic and aliphatic hydrocarbons. Degradability of oil products is dependent on the structure of the hydrocarbon molecule and therefore it is of importance to decide the composition of the contaminant. Mineral oil is most common not completely degradable and remaining heavier fractions always have a limited dissolving capacity in water. The risk is therefore limited due to the low mobility and low bioavailability. In such a situation the soil can contain high concentrations, while the groundwater contains low concentrations. However, the degradation of mineral oil resemble in general the degradation of a mix of aromatic hydrocarbons[132].

Transport

After a spill or leakage of a petroleum product such as gasoline, assuming the spill volume is sufficient, the free phase migrates downwards though the unsaturated zone until it reaches the capillary zone. As the free phase hydrocarbon moves through the subsurface, some of the liquid may be trapped in the soil or sediment pores as a residual saturation, or evaporate through volatilization. Since petroleum hydrocarbon liquids are less dense than water, they may accumulate and flow on top of the groundwater table. As the water table rises and falls through the seasons, the petroleum hydrocarbon on top of the groundwater table may follow, creating a smear zone of residual saturation. If the soil is saturated due to capillary rise of water, the NAPL will accumulate on top of the saturated zone. A range of physical, chemical and biological processes affect spreading of petroleum hydrocarbons that have reached the saturated zone. The most important processes affecting the fate of the organic compounds in groundwater are[133]:

- Dissolution from the NAPL phase into the passing groundwater
- Transport by advection and dispersion
- Sorption to the aquifer material
- Biological degradation by transformation and/or mineralization[134]

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[130] *VOCs* is an abbreviation for Volatile Organic Compounds.

[131] Fate and Transport of Petroleum Hydrocarbons in Soil and Groundwater at Big South Fork National River and Recreation Area, Tennessee and Kentucky, 2002-2003.

[132] Tauw, 2006

[133] Prommer, H *et al.* (2003)

[134] *Mineralisation* is used to describe the release of organic compounds during decomposition

As the dissolved plume moves, the concentration of the dissolved hydrocarbons is lowered by dispersion and dilution effects. Microorganisms may degrade hydrocarbons that are dissolved, volatilised or sorbed.

Mass transport in the saturated zone occurs mainly in the horizontal direction, typical in the direction of the groundwater flow. The dominance of influence of these processes varies strongly from the beginning of groundwater contamination to complete disappearance[135].

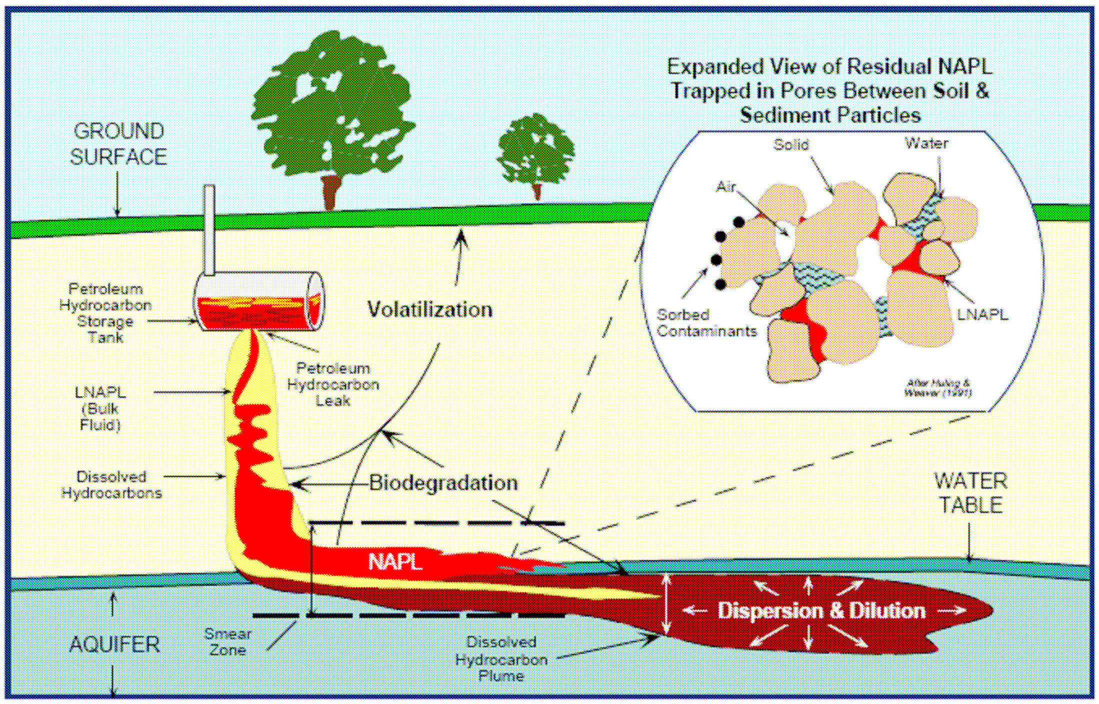

Figure 6.Transport processes of petroleum hydrocarbons (US EPA, 1999)

Degradation

The degradation of petroleum hydrocarbons is a reduction-oxidation reaction in which the hydrocarbons are oxidized[136]. The extent of hydrocarbon biodegradation in contaminated soils is critically dependent upon four factors, namely[137]:

- the presence of hydrocarbon degrading bacteria population
- the creation of optimal environmental conditions to stimulate biodegradative activity(such as temperature, moisture content**,** electron acceptors like O_2, NO_3^-, SO_4^{2-}, CO_2 or electron acceptors in mineral form , nutrients, pH)
- the predominant petroleum hydrocarbon types in the contaminated matrix and;
- the bioavailability of the contaminants to degradative bacteria.

Biodegradation rates of low to moderate weight aliphatic, alicyclic and aromatic hydrocarbons can be high if ideal conditions are present. Resistance to biodegradation in general increases as the molecular weight of the hydrocarbon increases[138]. Hydrocarbons with condensed ring structures, such as PAHs with four or more rings, have been shown to be relatively resistant to biodegradation. PAHs with only 2 or 3 rings (naphthalene, antracene)

[135] Prommer, H *et al.* (2003)
[136] Prommer, H *et al.*, 2003
[137] Cuypers, C., *et al.*, 2001
[138] Fate and Transport of Petroleum Hydrocarbons in Soil and Groundwater at Big South Fork National River and Recreation Area, Tennessee and Kentucky, 2002-2003.

are more easily biodegraded[139]. The so-called bioavailability of a chemical is determined by the rate of mass transfer relative to the intrinsic activity of the microbial cells. The bioavailability of a chemical is controlled by a number of physical-chemical processes such as sorption and desorption, diffusion, and dissolution. Particularly in old polluted sites, part of the contaminants appears to be inaccessible for biodegradation[140].

Chlorinated aliphatic hydrocarbons (CAHs)

Usage of CAHs

Chlorinated Hydrocarbons are man made chemical compounds of naturally occurring hydrocarbon constituents such as methane, ethane and ethene) and chlorine. The CAH is manufactured through various processes that substitute one or more hydrogen atoms with a chlorine atom. CAHs have been used for a wide variety of industrial applications. Due to their fat dissolving properties the main area of use has been as solvents and degreasing agents for instance for metals and in dry cleaning-fluids and as alternative to petroleum based solvents to eliminate fire risk[141]. CAHs include solvents such as tetrachloroethene (PCE), trichloroethene (TEC), carbon tetrachloride (CT), chloroform (CF), and methylene chloride (MC). Historical management and handling of products and wastes containing CAHs has resulted in contamination of soil and groundwater. Table 2 summarises the most common pollutant sources and their possible mobilisation for chlorinated solvents.

Table 12. Potential pollutant sources and possible mobilisation of chlorinated solvents (Swedish EPA 2006)

Pollutant source	**Mobilisation**
Storage tanks and drum storage	Spill from refilling of cistern. Leakage from cisterns, drums and pipelines
Process equipment	Spill from handling and leakage from the process equipment
Landfills and burial pits	Leakage from process waste, tipped straight on the ground or dumped in leaking drums
Sewage pipes	Leakage from sewage pipes or oil separators as free phase can gather at the bottom of the oil separator
Storm water system	Leakage from sand beds in storm water wells (free phase can gather in the sand beds)
Ventilation outlet	Condense from ventilation air

Physical and chemical properties of CAHs

CAHs contain solvents such as tetrachloroethene (PCE), trichloroethene (TCE), Carbon tetrachloride (CT), Chloroform (CF) and Methylene chloride (MC). Degradation products include dichloroethane (DCA), dichloroethene (DCE) and vinylchloride (VC)[142].

Most of the CAHs NAPLs are denser than water (except from vinyl chloride, chloroethane and chloromethane, which are gaseous in their pure phase under standard conditions) and

[139] ATSDR – toxic profile www.atsdr.cdc.gov/toxprofiles/tp123-c5.pdf
[140] Bosma *et al.*, 1997
[141] http://www.kemi.se
[142] http://www.epa.gov

have moderate aqueous solubility, why they are usually called DNAPLs (Dense Non Aqueous Phase Liquids) [143]. As the number of substituted chlorine atoms increases, molecular weight and density generally increase, and vapor pressure and aqueous solubility generally decrease. In general chlorinated solvents are high volatile and are low to moderate soluble in water. CAHs are also hydrophobic and the hydrophobic degree (log K_{ow}) increases in proportion with the number of chlorine atoms.

Transport

A CAH released in the soil, as pure organic liquid will strive to reach phase equilibrium[144]. CAHs will remain in free phase, adsorb to soil, dissolve in groundwater, or volatilise into soil gas.

When released in the subsoil, free phase CAHs will due to its high density (DNAPL) sink vertically by gravity through the saturated and the unsaturated permeable soils until they eventually reach the lowest point on top of a confining layer, such as clay layer. Migration will mainly be through easy pathways such as fracture in soil or bedrock or high permeable layers. This zone of free phase is the formation of contamination, which is called the source. Thereafter CAHs will spread in the same direction as the confining layer is leaning. In the unsaturated zone CAHs will migrate by diffusion of soil-gas vapour because of their high volatile properties. This may not only occur from the source area, but also from contaminated groundwater.

When it reaches the saturated zone a plume will be formed, as the CAHs will migrate by advection or dispersion with the groundwater or by diffusion as a result of concentration gradients[145]. Figure 2 presents these migration processes of CAHs in the subsurface. Therefore, remediation of chlorinated solvents focuses mainly on groundwater.

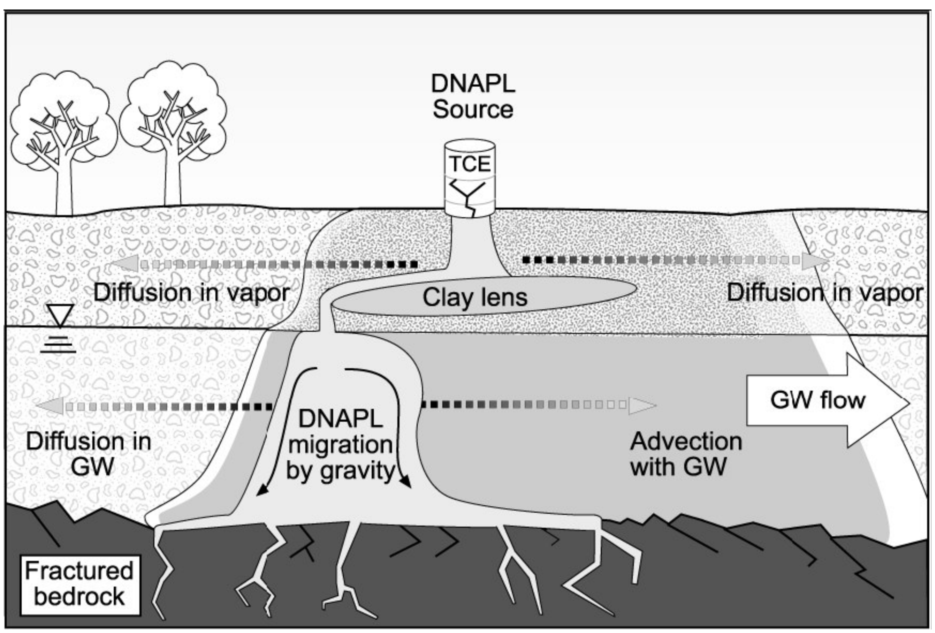

Figure 7. Example of CAH subsurface migration processes (US EPA, 2000)

143 *Ibid.*

144 *Phase equilibrium* is a condition in which all acting influences are cancelled by others, resulting in a stable, balanced, or unchanging system

145 Advection is

Degradation
Degradation of chlorinated solvents can occur by biological bacterial processes or by abiotic (nonbiological) mechanisms. Biological degradation dominates in most systems, depending on the type of contaminant and the chemical composition of the groundwater[146]. Biological degradation can be classified into following mechanism categories:

- Aerobic oxidation (direct or cometabolic)
- Anaerobic reductive dechlorination (direct or cometabolic[147])

Aerobic oxidation and anaerobic reductive dechlorination can occur naturally under proper conditions, but can be enhanced by addition of electron donors, electron acceptors, or nutrients in order to provide the proper conditions for aerobic oxidation or anaerobic reductive dechlorination to occur. Anaerobic reductive dechlorination is the most important degradation process of CAHs[148]. In this reaction bacteria gain energy as one or more chlorine atoms on a chlorinated hydrocarbon are replaced with hydrogen, as chlorinated compound serves as the direct electron donor. The mechanism is called sequential reduction of a chlorinated ethene or chlorinated ethane to an ethene or ethane, and is showed in figure 3. During the dechlorination hydrogen will be consumed and hydrochloric acid is produced.

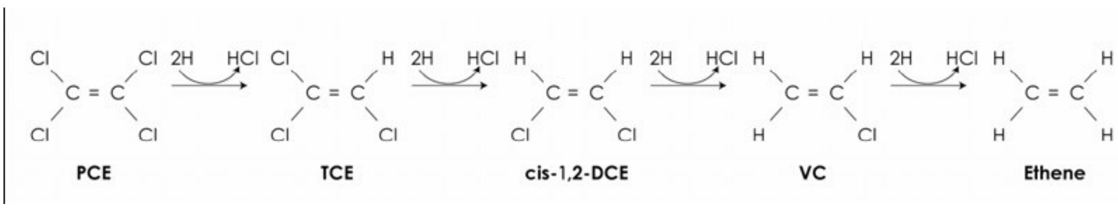

Figure 8. Sequential anaerobic reductive dechlorination of PCE *(Swedish EPA, 2006)*

The dechlorination process occurs faster of the more chlorinated CAHs (PCE and TCE) than the dechlorination of less chlorinated CAHs. Dechlorination during anaerobic environments will result in even more toxic compounds like dichloroethene (DCE) and vinylchoride (VC) are produced an accumulated in anaerobic environments. VCs are commonly degradated during aerobic conditions and enhanced aerobic bioremediation can be implemented to degrade the VC[149].

[146] US EPA, 2000
[147] *Cometabolic degradation* is when the CAH degradation or oxidation is caused by an enzyme or cofactor produced during microbial metabolism of another compound.
[148] US EPA, 2000
[149] *Ibid.*

Appendix 5 / Case studies

1. Arvehälls dry cleaning site

Country
Sweden

Contamination
Perchloroethene (PCE)

Technique
Vacuum extraction
Pump&treat

Project status
Completed 2002

Background
The site is located approximately 1 km from the town centre of Lerum, in a small industrial area. Due to the expansion of the upper secondary school, Lerums municipality acquisitioned the former dry cleaning site next to the school. The dry cleaning activity was operated on the site during the last 30 years, causing a contamination of perchlorethylene mainly in soil and groundwater. The dry cleaning activity had gone bankruptcy and Lerums Municipality took the responsibility to remediate the site. The project was financed to 50 % of the municipality and 50 % from the county administrative board. After conducted site investigation a remediation was started in 1999 in order to reduce and hopefully abate the contaminants under the building. The building was renovated for school uses.

Site investigation
Conducted site investigation included 21 soil samples and 3 groundwater samples analysed regarding PCE, investigation with ground penetrating radar for mapping of groundwater surface and slope. Pore gas measurements were also conducted. Supplementary pre studies had to be conducted in order to decide hydrogeological parameters, including pump tests in order to decide possible pump volumes, and modelling of the groundwater currents in order to decide rate of discharge.

Pollution situation and ground conditions
The ground was mainly flat. Behind the railway running along the south border, the ground was steeping down to a creek with high environmental protection value. The geological upper soil layers consist of 8-10 m of stratified sand- and silt layers overlaying a massive clay layer. The different soil layers have different permeability. The upper soil layers are considered permeable. The groundwater table is estimated to approximately 5 m below ground level. Previous site investigation shows a slight water divider under the building on the site. The area is today sealed with asphalt to a great extent. The area is filled up to approximately 1 m of coarse fill material.

There contamination was probably caused from spillage when storing and handling PCE outside the building and leakage through the bottom plate in the building due to careless handling indoor. PCE in wastewater had reached the soil by leaking sewerage pipes and sewerage wells.

Contaminated soil is mainly encountered under the building and in the vicinity to existing sewerage pipes. Contaminated soil was most likely to be found deeper than 3 m below ground level in a zone of 20*60 meters in direction from southwest to northeast under the site. Contamination levels encountered ranged between 120- 330 mg/kg TS. Concentration of PCE in groundwater was between 1,1 mg/l and 5,2 mg/l. A total amount of 400 kg solvents was estimated to be present in the ground. Pore gas contained concentrations of VOC over 2000 ppm under the bottom plate of the building and slightly west and east of the building.

No contamination was found in the top layers. The highest concentrations were found in the sewage ditches. Potential pathways were downward migration of contaminants through sand- and silt layers to underlying clay layer or locally present layers of high permeability. Migration also occurred through the fill layer in the sewage ditches.

There where uncertainties whether the contamination had migrated to deeper layers in the ground, and whether contamination had reached pockets of groundwater at relatively great depths.

Remediation goals
The remediation goals were to reduce the contaminant levels and hopefully remediate the contamination under the building. For soil the goal was set to 20 mg/kg d.s, for groundwater 0,04 mg/l and for the pore gas in the inspection wells 50 mg/m3. These levels correspond to the Swedish EPAs generic guideline values for less sensitive land use with groundwater protection (MKM GV).

Selection of remediation technology

The chosen remediation method was Soil Vapour Extraction of the unsaturated zone and Stripping of extracted water with cleaning through an active coal filter. The measure was focused on remediation of contaminants under the present building. No physical operations would be done on the building and normal activity had to be possible without interruptions from on-going remediation.

Results
The remediation was interrupted in 2002 when 1,4 tonnes PCE had been abated, which is approximately three times as much the amount estimated in the site investigation. The remediation goals regarding concentrations of PCE in soil and groundwater were not achieved. The remediation goal for levels in indoor air in the school building was achieved. Discussions have continued after the remediation whether the remediation should continue or not. The appraisal from the authorities is to continue the monitoring of indoor air in the school building. Decision will be taken regarding further remediation after a further site survey with the intention to investigate the geohydrological conditions on the site, the spreading of PCE and to identify the amount of PCE still present in the ground.

Experiences
The chosen solution was working well due to correct conclusions from the conducted site investigation. The pre-study could have been wider to be able to better calculate on the risks for spreading outside the area of the remediation.

2. Former petrol station Götene

Country
Sweden

Contamination
TEX
Aromatics

Technique
Vacuum extraction
Bioventing

Project status
March –July 2003

Background
Distribution of fuels has been going on at the site since 1961. Due to an owner change of the petrol station an investigation of the site was carried out revealing oil pollution in a limited area of the site. Remediation was necessary due to risk for environmental or human exposure and further spreading of contaminants with the groundwater. As purchase of clean site was included in the purchase agreement and, the previous owner undertook necessary remediation measures of the site.

The site is located in the central part of the community, close to a dairy factory. The site is mainly covered with asphalt and concrete bricks. The terrain in the area is flat. On the site there were several buildings and installations such as a station building, pumping stations and four underground cisterns.

Site investigation
Soil samples where taken in 19 points of which 3 where analysed in laboratory. One groundwater sample where analysed.

Pollution situation and ground conditions
The soil was stratified with varying layers of coarse sand/sand overlaying a clay layer of over a more permeable layer of gravel, sand and silt. The clay layer was 0,5-1 m thick and encountered at 2,5 m below ground level. Depth to groundwater table is 3.5 m from ground level. The direction of groundwater flow was hard to estimate, due to the relatively flat topography.

Petroleum contaminants where encountered in both soil and groundwater, next to the underground tanks. The contamination was encountered in 3m depth and was transported with the groundwater in the permeable layer under the clay layer. Concentrations encountered in the soil where Σ TEX 650 mg/kg d.s., >C8-C10 4300 mg/kg d.s. and >C10-C35 74 mg/kg d.s. Contaminants of high concentrations encountered in the groundwater were Sum canc. PAH 0,83 µg/l and sum other PAH 1,7 µg/l. Potential pathways for the contaminants were spreading with groundwater in the permeable layer under the clay layer.

Remediation goals
The remediation goal for the site was to reduce the contamination level to less than the generic guideline value for the classification *MKM* (less sensitive land use) corresponding to normal permeable soils for petrol stations by the Swedish EPA.
Selection of remediation technology

Excavation was not an option since the petrol station should be able to operate during the remediation. The remediation should focus on both source and plume. The technique was introduced through personal contacts and no other solutions were discussed. The main reasons influencing the choice was that the technique would not disturb the on-going activity. In-situ remediation was also considered to be a more safe solution with a smaller risk for damage on the constructions at the site.

Performance
Remediation with vacuum extraction in combination with bioventing was performed. The ground was ventilated and soil vapour was extracted and an active coal filter cleaned extracted groundwater. Control of the conditions for biological degradation was made as the extraction unit was installed, indicating low concentrations of nitrogen. A nitrogen-rich solution was added to the cleaned re-injected water in order to increase the biological activity in addition to the increased oxygen content in the ground as a result of the bio venting.

9 ventilation wells were installed and used for injection of air, extraction soil vapour, extraction and re-injection of groundwater.

As part of the standard agreement between the stakeholders, the contractor was obligated to report eventually contaminant spreading during the remediation. A back-up plan was not prepared.

Results
During the remediation approximately 300 kg pollution was destructed, partly via filter with active coal and partly by biological destruction in the ground. After 5 months the results indicated that the remediation goals successfully had been achieved.

Experiences
This was the first case of in-situ remediation for the municipality to process. Experience of the petroleum branch from earlier SPIMFAB projects and the fact that the remediation was limited to a smaller area which would be easier to control, made the local authorities secure with the solution.

3. Former petrol station Haninge

Country
Sweden

Contamination
Petroleum products

Technique
(Phase 1) Air sparging and biological degradation
(Phase 3) Excavation
(Phase 2 & 4) Pump&treat with biological degradation

Project status
2001-2005

Background
A petrol station was operating on the site in 1963-1990. The activity had caused a very large petroleum contamination in soil and groundwater. The site was at the time of the remediation used as parking space and recycling station. A change of land use was planned for the future to commercial purposes and office buildings and there was a risk for human exposure in future buildings. SPIMFAB[150] discovered the pollution in a regular site investigation and conducted the remediation of the site.

Site investigation
Before the in-situ remediation started in 2002 a site investigation was carried out in order to determine the contaminants and the dimension of the plume. Soil sampling was made in 14 points and groundwater from 7 wells. Only groundwater samples were analysed in laboratory and the hydraulic conductivity was measured with a *slug test.* After the initial remediation a supplementary site investigation was carried out.

Pollution situation and ground conditions
The soil in the area is mainly sand. Groundwater level is normally 3,5 m below surface level but varied during the remediation. The groundwater flow was estimated to a north east direction and the hydraulic conductivity was measured in three locations showing moderate to low conductivity.

Results from the first site investigation in 1999 indicated that 3000 m3 soil was contaminated with petroleum. Leakage from installations in the ground and spill was the probable cause of the pollution. A source area was encountered in the vicinity of the previous underground tanks and pump area. A contamination plume was identified towards north-east in the direction of the

[150] SPIMFAB

groundwater flow towards the neighbouring parcel. During construction works on this site an old oil container was found in the ground used as a sewer of an oil separator to the petrol station. High concentrations were encountered in the vicinity of this container. Maximum concentrations in the source area were Aliphatic hydrocarbons: 4700 µg/l, aromatic hydrocarbons: 20 000 µg/l, >C8-C10: 3200 µg/l, >C10-C35: 600 µg/l and PAHs; 170 µg/l. The contamination was encountered from 2 to 4, 5 m below surface level.

Remediation goals
Site specific target values were used due to site specific circumstances on the site. The values correspond to a factor 2-3 of the guideline values of the branch specific values.

Selection of remediation technology
A main criterion for evaluation of different solutions was the total cost of the remediation. The cost of an in situ strategy was compared with total excavation. A total excavation would be more expensive and included costs for approximately 1.000.000 SEK (110.640 EURO) more than an in situ remediation due to transport- and ex site treatment costs. In situ remediation with the Buster method was chosen, as it seemed to be suitable for the known conditions.

Performance
Phase 1: During 2000-2001 the ground was remediated with vacuum extraction of soil vapour in the unsaturated zone, down to 3,5 m and volatile hydrocarbons were incinerated in a catalyst. Cleaned and warm air was re-injected in the saturated zone, sparged into the unsaturated zone where it could be extracted or undergo biological degradation. A total of 5 pumping wells were used in which soil vapour was extracted and cleaned. 7 ventilation wells were used for the re-injection of clean air. Each well ventilated a radius of 4 m in the ground. Groundwater was extracted in three lines crossing the remediation area and cleaned through a sand filter followed with 2 active coal filters. The clean water was then transferred to the local sewage system.

Phase 2: Groundwater remediation in means of pump and treat where injection of biological stimulating nutrients was injected. The system consisted of extraction- and injection unit.

Phase 3: Excavation of contaminated soils

Phase 4: The remediation continued in march 2003 with groundwater pump and treat with biological treatment, which was completed in July the same year.

Results
Phase 1: Remediation control showed high concentrations of volatile aromatics in an area northwest of where the underground tanks were previously situated. Excavation was carried out down to 3,0-3,5 m. During the excavation the contamination was found larger than estimated. A total of 3000 m^3 groundwater was extracted and 240 l petroleum hydrocarbons were abated. 113 tonnes of soil was excavated. Totally 6100 kg petroleum products were abated from soil. Residual contamination of petroleum hydrocarbons was estimated to be locally present and the contractor added nutrients and bacteria during the autumn 2002 in order to increase the biological degradation and support future groundwater remediation.

Phase 2: Controls showed continuously high concentrations in the groundwater in the area. In particular high concentrations were found in the source area at the fluctuation zone at 3,2-4 m below surface level. The groundwater situation had not improved and the hot spots were suspected to be larger than estimated. The remediation of soil was sufficient.

Phase 3: A total of 5250 tonnes of soil was excavated. During the excavations a concrete container was found in the ground and a concrete floor which was heavily contaminated and transported to a treatment plant.

Phase 4: A total of 57 kg of petroleum product was remediated from the groundwater. The remediation goal was not achieved, but further remediation was not considered as reasonable since the concentrations in groundwater could be correlated to the residual concentrations in the soil. A decreasing trend in the concentration over time was established proving a further decrease could be possible.

Experiences
The total dimension of the contamination was not defined properly and appeared to be larger than estimated from the beginning.

4. Petrol station Bottnaryd

Country
Sweden

Contamination
Petrol
Gasoline
Diesel

Technique
Chemical oxidation with KEMOX

Project status
2005

Background
Ongoing activity in the site was a petrol station and a restaurant. Leakage from supplying pipes had caused petroleum contamination in soil and groundwater and the petrol company was responsible for remediating the contaminants. The site is located on forest ground with rather flat terrain. On the site there is a petrol station and a restaurant. A pump station with a three-chamber well is located east of the station building outside the actual area of remediation.

Site investigation
In 2000 and 2002 site investigations were conducted. 13 respective 25 soil samples where taken and analysed with a PID-instrument in respect of VOC. Nine samples were analysed in lab in respect of BTEX. Two groundwater samples were analysed with respect of BTEX and aliphatic hydrocarbons, and aromatic hydrocarbons.

Pollution situation and ground conditions
The natural soil consists of sandy till. Due to previous remediation, the upper 2 m consist of fillings of sand and an underlying macadam layer of 0,2 m. The groundwater surface was encountered at 2,7 m below ground level.

The contamination was mainly benzene above the guideline value and heavier hydrocarbons such diesel. The contamination was located at a depth of 2-3 m below surface level east of the underground tanks. Leakage from supplying pipes was the probable source of the contamination release. The contaminated area had an upper surface of 650m^2 and the amount of contaminated soil was estimated to 960 ton. The remediated soil was encountered at a depth of 1,8-2,8 m below surface level. Maximum concentrations of TEX were between 231 and 1561 mg/kg. ds. Also some elements of free phase petroleum was encountered.

Remediation goals
The goal of the remediation was to achieve an improved contamination situation on the site and decrease the risk for impact on the surroundings by horizontal spreading of the contamination with the groundwater. The guideline value for less sensitive ground (MKM) for permeable soils was used as remediation goal.

Selection of remediation technology
Different remediation techniques were investigated:

- Biological in situ
- Ventilation
- Pump and Treat
- Excavation

Criteria for the evaluation were the price, the environmental impact, and duration of the remediation. Chemical oxidation was considered to be the best option since it would have the least environmental impact and in comparison to excavation it reduced transports and use of native materials. The choice of oxidant in granulates was made because it was easier to handle and did not involve the same restrictions as oxidant in liquid phase. Liquid oxidant would give a stronger reaction and is would therefore be more difficult to control.

Performance
The oxidation was carried out with sodium percarbonate and peroxide added to the soil diffundating with the groundwater. The oxidant is released slowly which leads to a slow oxidation of the contaminant. In order to design the full-scale remediation, a laboratory study was carried out. followed by a pilot test on a 5*5 m area on the location. The tests were conducted in order to verify the design and to optimise the amounts of granulate in respect to groundwater, soil type, and

contamination and to get an idea of remediation duration and the decomposing process. The duration of the remediation was 5 weeks and included lowering of the groundwater, relieve of soil masses, mixing with the oxidation granulate. As the petrol station was operating during the remediation, relieve of soil masses and treatment was carried out step by step in smaller areas. Extracted groundwater was treated in a mobile treatment plant, where after the water was transferred to an infiltration basin. Due to the lowering of the groundwater table, relieve of the contaminated soil was possible. The granulate was mixed with the soil in the shaft. Clean soil was reused to refill the shaft. The duration of the treatment of one shaft was approximately 4 days.

Results

Control sampling indicated that concentrations had been reduced below the remediation goal, except for the fraction >C8-C10. In two of the four shafts free phase of petroleum products still occurred in groundwater and some hot spots after the treatment. In these shafts a more durable treatment with oxidation granulates and pump- and treat of groundwater was conducted. The results from control sampling indicated that more than 70 % of the contaminants were decomposed or approximately more than 700 kg of petroleum hydrocarbons. The remediation had been most effective on reducing the levels of Σ TEX. Groundwater samples were analysed on eco-toxicity before, during and after treatment and fond non-toxic.

Experiences

The chemical oxidation is most intense during the first 24 hours but continues during several weeks. There where no immediate spreading of contaminants with the groundwater flow, caused by the remediation. Residual contaminants in hot spots could be due to the fast chemical reaction in the soil. When liquid oxidant is used, the decomposition of the available contaminants in the groundwater is immediate, but less available contaminants in soil may not be oxidised. The advantage of using this technique is the slower reaction due to slow diffusion from the granulate.

This was the first experience of in situ chemical oxidation in the municipality and the authorities were in compliance with the use of the new technique. A continuously dialogue were held between the stakeholders and since the techniques was considered more environmental friendly than excavation the authorities were positive of using it.

The application of the technique requires compulsory permit but after negotiations with the authorities, the activity only required to be reported to the municipality. The contractor means that this opens up the possibilities for similar remediation at other sites in the country.

5. Former petrol station Boden

Country
Sweden

Contamination
Aliphatic hydrocarbons
Aromatic hydrocarbons
PAH

Technique
In situ ventilation
Steam injection
Pump&treat
In situ chemical oxidation with peroxide
Excavation

Background

Between 1960 and 1984 a petrol station was operating at the site. The activity caused high concentrations of aliphatic and aromatic hydrocarbons, and PAHs in soil and groundwater. The Municipality of Boden reported the former petrol station to SPIMFAB[151] to investigate it and further on conduct a remediation. The site is located in the central part of Boden. Today there is a grocery shop on the site. The site is adjacent to apartment complexes and a park area. The creek Bodån runs 600 m south east of the location. The area is sealed with asphalt. Due to bad ground conditions, the building on the site is built on foundation piles. All underground tanks have previously been removed. The area is rather flat with a slight slope towards south-east.

Site investigation

Drilling were done in 10 points down to 7,1 m. The soil was analysed in the field with a PID-instrument. 5 soil samples from 3 points were lab analysed.

Pollution situation and ground conditions

Sand and fine sands dominate the soil in the area. The first 2,5 m is filled with coarse sand. The natural soils under the filling consist of 1-2,5 m of silt followed by a 9-13 m layer of sulphide clay

[151] SPIMFAB = Svenska Petroleum Institutets Miljösanerings Fond AB (the Swedish Petroleum Institutes Remediation Fund).

Project status
March 2000-May 2001

down to firm moraine.
The groundwater table varies during the year between 2,4 to 4,8 m below ground level. Due to low permeable soils on the depth, the groundwater flow was limited.

The guideline values for soil for aliphatic, aromatic hydrocarbons and PAHs in soil were exceeded in all samples. The contamination was encountered on 1,7 – 6,0 m depth within a surface area of 200 m2 between the building and the street. The source area was located close to the former pump and underground tank. The dimension of the contamination in the saturated zone was in a range of 400 m3 and 200m3. In the soil next to the former underground tanks the concentrations of volatile aliphatic and aromatic hydrocarbons were high and the risk for spreading via underground pipes nearby was high. Maximum concentrations encountered in soil were for aliphatic hydrocarbons: 3800mg/kg.ds, ΣTEX; 1160 mg/kg.ds, >C8-C10: 1700mg/kg.ds, PAH other than carcinogenic; 29,8 mg/kg. ds. The groundwater was contaminated with aliphatic, aromatic hydrocarbons and MTBE. Maximum concentration encountered were total extractable aliphatic hydrocarbons; 21.000 µg/l, aromatic hydrocarbons; 6000µg/l, ΣBTEX; 11.000µg/l and MTBE 1800µg/l. Due to the low permeable soil the spreading in the groundwater was estimated as limited.

Remediation goals
Remediation goal was to reduce the levels in soil and groundwater to the guideline values for the land use category less sensitive ground (MKM) for petrol stations.

Selection of remediation technology
The choice of solution was between total excavation and in situ remediation. In situ by venting and chemical oxidation of the saturated zone was chosen. The reasons to why this solution was chosen was because it was a rather new technique and interesting to try, the volume of contaminated soil was large and was situated close to, and perhaps even under the building, which would make it difficult to excavate. For these reasons in situ was estimated as a cheaper solution than excavation. In situ remediation would also have less impact on the on-going activity at the site, than an excavation. The discussion about pollution caused by transports in relation to the amount remediated was also having influence on the selection. Venting and chemical oxidation was techniques suggested by the contractor. A lab scale test was carried out in order to assess the possibility to apply chemical oxidation.

Performance and results
From march 2000 to September 2001 the ground between 1,7 – 6,0 m was remediated with soil ventilation and pump and treat according to the Buster method. 5 ventilation wells were installed. One of these was combined ventilation and pumping well (two-phase well). Groundwater was extracted in one well and cleaned through an active coal filter and transferred to the local storm water system. Approximately 16 m^3 of groundwater was extracted and treated. Extracted soil vapour was cleaned by catalysed incineration. In august, steam was injected by steam injection skewers in the most contaminated area, in order to speed up the biological degradation of oil. During the in situ remediation the levels of VOCs and CO_2 was monitored, which indicated continuously low levels. Control sampling indicated that the remediation goals had not been achieved and remediation with in situ chemical oxidation with peroxide followed in May 2001. Peroxide was injected in five wells and groundwater was extracted in a centrally placed extraction well. In June 2001 the remediation goals where not achieved and remediation was completed by excavation. Excavation down to 4 m within a 180 m^2 large area was carried out. Totally 200 m^2 contaminated soils was excavated and transported to a treatment plant. Due to limited groundwater flow, the excavations were carried out without any groundwater extraction.

Results

Experiences
The response from the authorities was positive. SPIMFAB was also positive to the chosen solution because of the reduced transports, but some how not convinced that the method would work as planned. For that reason they demanded a fix price from the contractor for the total remediation. They considered the solution positive due to the need of less transport.

The main reason to the failure of the venting was probably the low permeable soils, which the consultants suspected from the beginning could cause problems. But regarding the good results from tests carried out on the neighbouring site, the contractor considered the site conditions suitable for the method. Probably the ventilation only affected a limited volume in the ground.

The chemical oxidation proved good results in lab-scale tests on soil samples from the site, but in the field only a marginal difference in concentrations of the contamination could me measured. The only difference measured was a change in the composition of the contamination.

6. Two sites in the inner city of Utrecht

Country
The Netherlands

Contamination
Perchloroethene (PCE)

Technique
ISCO by C-sparge™
Pump and treat

Project status
On-going (2007)

Background
The two sites are located close together in a residential area in the historical inner city of Utrecht. Historical metal handling activity at the sites caused two contamination source areas with volatile chlorinated hydrocarbons (VOCls). Metal handling activities were operated at two sites in the area from the 1920ies until 1995, using VOCls (tetrachlorethylen) for degreasing metal in the production processes. Removal of pollutant sources and remediation of source areas by Soil Vapour Extraction and groundwater remediation was carried out in a previous attempt without success. Due to installation of new apartments and the establishment of gardens the sites are remediated by public means, commissioned by the municipality of Utrecht. The first site is situated under a historical building along one of the canals in Utrecht. The other site is situated in an enclosed inner terrain in the residential area. The only access to the site is a low gateway and the hallway through an apartment.

Site investigation
Several soil surveys and plans have been made during previous years (1987-2007), mainly by manual drilling where two source areas were detected. Supplementary investigations for the planned in-situ remediation included to actualise and further define the contamination situation if VOCls were present in the groundwater and to establish if and where there was a soil contamination present. 13 soil samples and 26 groundwater samples where taken for laboratory analysis.

Pollution situation and ground conditions
0-5 m below ground level top confining layer with fill/peat/sand/clay. 5-40 m below ground level sandy aquifer. The groundwater surface is located to approximately 4,5 m below soil surface and the groundwater flow is towards the canal (north-west).

The historical degreasing activity had resulted in soil- and groundwater pollution of mainly chlorinated solvents (VOCls), but also heavy metals and PAH is present due to urban living. Spill and leakage from process machine, sewerage and cesspools had caused source areas of VOCls at two locations. One contamination source was located beneath the cellar to the historical building, and the other beneath the enclosed inner terrain of the residential area. The source volumes had the dimensions of 210m^3 respective 225m^3 (15*7*2 m and15*30*0,5 m). The volume of groundwater with concentrations over the intervention value was assessed to 60 000m^3. Concentrations of PCE encountered in the soil ranged between *1-2,7 mg/kg ds*, and in groundwater approximately *85-2700 mg/l* beneath the cellar and up to *4900 mg/l* under the enclosed terrain.

Remediation goals
Main drivers of the remediation are the installation of new apartments and the establishment of a garden in the inner terrain. The goal is to reduce the risk for human exposure via soil vapour and further diffusion of the VOCls. The remediation approach is an integrated, function oriented and cost-effective remediation with focus on bulk-removal of source areas during a period of 1-3 years. The ALARA[152] principle has to be followed for the abatement of the source area. A stationary situation must have been reached within 5 years and stable end situation must be reached within 15-30 years.

Selection of remediation technology
The accessibility to the source areas was limited and extraction of large groundwater quantities was not feasible due to settlements in the soil (peat/clay) which could damage the buildings.

[152] ALARA = As Low As Reasonable Achievable

Several remedial options where discussed; Pump- and treat, co-solvent flushing, in situ biological degradation, in-situ chemical oxidation. Chemical oxidation with C-sparge for remediation of the source areas together with co-solvent remediation of plume areas where chosen. The main reasons of the selection were that the municipality had good experience with C-sparge from earlier remediation and wanted to try it again. Excavation of the source areas was not an option since that had already been done and the site was rebuilt. The other remedial options where approved as part of a back-up plan in case that the chosen techniques did not succeed.

Results

Experiences

7. Fuel depot in Markelo

Country
The Netherlands

Contamination
Mineral oil
BTEX

Technique
Excavation in combination with biosparging and soil vapor extraction

Project status
2002-ongoing (monitoring)

Background
The site in the eastern of Holland is a large fuel depot, from which kerosene is transported via pipelines towards air bases in the Netherlands as well as the civil air fields of Schipol Amsterdam and Frankfurt in Germany. As a result of leakage during a longer period of time and rupture of pipes, severe contamination with hydrocarbons was present. Renovation works for the manifolds and pipelines gave an opportunity to remediate contaminated soil in combination with regular maintenance works. The ministry of defence financed the remediation. The site has an area of approximately 3 ha and is located next to a field in an agricultural area. The closest neighbours are farms with houses. At the site 7 large fuel tanks of 10 million m^3 are present in the ground. The terrain surface is varying at the site.

Site investigation
Previous investigation conducted several years ago, did not cover some of the more critical spots, such as manifolds etc. In order to define the actual borders of the contamination a supplementary site investigation was carried out. 55 additional sampling points were made with drilling. The supplementary investigation resulted in expanding of the excavation plan.

Pollution situation and ground conditions
The site is situated in the central sand area of Holland with mainly compact sandy and loamy soils with specific weight of 2000 kg/m^3. Fine sand with loamy parts was encountered down to 4,5 m. Between 4,5 to 45 meters coarse high permeable sand was encountered. The groundwater is varying between 2 to 3 m below ground level. The local groundwater flow is below 4,5 meters in the direction towards southwest.

Two different contaminated areas where found. One with an older contamination and one with a more recently caused contamination. The ground was contaminated with mineral oil and volatile aromatics in concentrations up to 8000 mg/kg.ds in the soil and 10 000 µg/l in the groundwater. The contaminants origin from multiple sources *e.g.* leakage of pipes, resulting in a source area of totally 30 000 m^2. Highest concentration was found just above the groundwater surface as free phase. Contaminants where found at a deep of maximum 5 m. No plume had been formed due to the compact soil.

Remediation goals
Remediation goal for the old contamination was to decrease the contamination level until the *average value*[153] has been reached. Focus of the remediation is the total abatement of the source area and plume until stable end situation has been reached. Two locations with old pollution were remediated with a function-oriented and cost-effective approach for mobile pollution. Remediation goal was maximal but cost/effective remediation of the mineral oil and volatile aromatics. Total remediation of the source area and stable end situation for the rest. One location with new pollution fell within the frame for obligation of remediation and had to be remediated completely, with the

[153] Average Value = (Target Value + Intervention Value)/2

target value as goal.

Selection of remediation technology

Starting point for selection of remediation was to prevent further spreading of the contamination, function oriented remediation (the goal is set regarding the present and future soil use of the site), and maximal and cost/effective remediation of the contamination. The activity at the site could not be interrupted since the depot is a very important provider of fuels in the Dutch army and the depth of excavation works was limited due to mechanical limitations in the ground.

Selected remediation techniques suitable for the site where:

- Excavation of surface layers
- Groundwater extraction
- Soil vapour extraction under building
- Air sparging/bio sparging

No real evaluation of different techniques was carried out. The ministry of defence had earlier positive experiences of this selection of techniques for remediation of air fuel depots which was crucial in the decision of remedial solution.

Performance

From April 2002 to July 2003 the excavation of 16500 m3 strongly contaminated soil was carried out. Excavations down to 0,5 m below groundwater level were made. Groundwater was remediated to a small extent by means of groundwater extraction. Low capacity on the local sewage system limited the use of this technique and it could mainly be used to remediate the free phase contamination. After the excavation there were still contamination left and an Air Sparging in situ system was installed to stimulate biological degradation.

The whole remediation included

- excavation of 16.500 m3 highly contaminated soil. A total of 34.000 tonnes.
- extraction of 1.680 m3 groundwater, transferred to the local sewage system
- cleaning and scrap of an oil separator

The installation of in situ system included: 810 m horizontal drains, 110 soil vapour extraction filters to 2 m below ground level, 174 air stripping filter to 6 m below ground level and accessories. High concentrations of BTEX (a.o. benzene) caused potential risks of explosions and exposure to humans.

Results

The soil remediation was successfully completed. Within 2 years approximately 80 % of the contamination had been abated. The concentrations after the remediation are for soil 500-1000 mg/kg.ds. and for the groundwater 300-600 µg/l. The average value had been reached within the main part of the area. Two sites showed locally high concentrations (due to free phase contamination) and are today being remediated by groundwater extraction. The site is still monitored.

Experiences

The compacted sand resulted in a horizontal flow of injected oxygen instead of vertical. The injected oxygen pushed the groundwater, leading to rising groundwater levels in adjacent areas and spreading of the pollutants.

During the remediation a lot of energy was required. The cost only for the energy was up to 100.000 €/year. Total cost per cubic meter remediated soil was approximately € 4500.

One factor to take into account when estimating the time required and the cost for the remediation is the efficiency of the injection pumps. The pumps are only effective 90 % of the time due to maintenance and stabilisation of levels in the ground. A smooth program that air sparging injects air in 5 minutes and pauses in 55 minutes.

8. Fuel loading station at a military site Ermelo

Country
Sweden

Contamination
Diesel

Technique
ISCO by Fenton's reagent
Soil Vapour Extraction
Triple phase extraction

Project status
1999-ongoing

Background
The site is located in a fuel loading station in a military area in Ermelo. An accident in October 2000 with a broken pipe has caused severe ground pollution to a deep of 12 meter below ground level. Since it was a newly caused pollution (after 1987), the ministry of defence was responsible for a total remediation. The site is located in a military terrain. Recently two underground tanks of 25.000 l and 60.000 l were installed for supply of benzene and gasoline.

Site investigation
Soon after the accident the investigation started. Grass on the surface where the leakage had occurred had turned yellow why the contaminated area could easily be estimated to 50 m^2. Shallow samples were taken and three deep drillings with sampling where carried out within and outside the contaminated area.

Pollution situation and ground conditions
The site is situated in the central sand area of Holland. The soil consisted of a deep homogenous sand layer with elements of gravel and loam lenses. Groundwater table was found at a depth of 12 m below ground level.

In the accident approximately 6000 litres of diesel had entered the soil system. Mineral oil and volatile aromatics were found in the site investigation. The contamination was quickly transported downwards due to the sandy soil layer. The contamination source reached down to approximately 13 m below ground level. A free phase contamination was encountered on top of the groundwater surface. Maximum concentration of mineral oil encountered in the soil was 29 000 mg/kg.ds. Free phase oil was encountered on top of the groundwater surface. BTEX encountered in the groundwater had maximum concentrations of 1,6 mg/kg.ds.

Remediation goals
Since the pollution was caused after 1987 a total clean up was required. The goal was to clean up the site as far as possible with the goal to reach the target value.

Selection of remediation technology
Remediation was focused on both source area and plume. Only a brief evaluation of techniques where made. Remediation by chemical oxidation was a rather new technique at the time of the evaluation. More conventional techniques were considered to be too slow and not having enough capacity to achieve the remediation goal in time. Especially biological techniques were not efficient in such high concentrations. Electro reclamation was an expensive option for remediation below groundwater surface. A fast remediation solution was required since the on-going activity at the site could not be interrupted. A rather aggressive solution was required and removal of free phase with triple phase extraction and further chemical oxidation was selected due to the on-going fuel loading activity and the depth of the contaminant. The main reason of selecting in situ chemical oxidation was the great depth of the contamination and the need of a technique that could perform a total clean up in the saturated zone of both source and plume. It was very important that on-going fuel loading activity could continue at the site during remediation and for that reason in situ chemical oxidation was a good option. The fuel tank present in the ground was new and it was not an option to remove the tank and excavate, since it was a very important fuel loading station. A small pilot test on an area of 5 m^2 was conducted before a full-scale remediation was performed. The results were satisfying and the authorities gave their approval in the year of 2000. A full-scale remediation followed.

Performance
The intensive remediation was carried out during 1,5 years in three parts: excavation of 120 m^3 strongly contaminated soil around the tank (down to 0-2 m below ground level), extraction of 1600 m^3 pure product from 15 triple phase extraction filters-, and injection of 60 tonnes oxidants via 29 injection filters (1 injection well each 5m^2).

Results
The remediation goal was not achieved and locally there were still high concentrations. Due to the fast flow of groundwater there was a risk for spreading. The contractor could not perform further

reduction with the technique and in order to prevent spreading a groundwater extraction well was installed. After 2 years of monitoring the levels have decreased gradually. At this point the results were at acceptable levels. Monitoring though is still needed. The final cost of the remediation was higher than estimated. Remediation cost was totally 227.999 € = 4500 €/m2.

Experiences
The sandy soil with gravel caused fast rising of the oxidant through the ground, which affected the chemical oxidation. Shorter contact time between contaminant and oxidant reduces the oxidising effect. As an effect of the chemical oxidation the biological activity increases due to increased oxygen levels and raised ground temperature, which was probably the reason to the decreasing concentrations observed during monitoring. The loam lenses could also be one reason to why the remediation goal could not be reached, since they probably contained high concentrations and were difficult to remediate.

9. Oil pumping station Oosterhout

Country
The Netherlands

Contamination
Mineral oil
BTEX
Volatile aliphatics

Technique
ISCO with peroxide
Soil vapor extraction
Air sparging

Project status
2004-ongoing

Background
From the harbour in Rotterdam there is since 1966 a pipeline transporting nafta oil to Beek in Limburg further on to Germany, known as the Botlek pipeline. In 1971 an unmanned pumping station was connected at Oosterhout, half way the pipeline. During the installation the pipeline were cut in two places resulting in two spills contaminating as well soil as groundwater. There is no human or ecological risk present, but due to risk for spreading a remediation of the site was considered as urgent. The remediation was partly financed by the pipeline company, and partly (up to 1/3) subsidised by the government since the contamination probably had been caused before *1975*.

The site has a total area of 3200 m^2 and is located in an agricultural area with farms surrounded by pastures.

Site investigation
Site investigation was carried out at five occasions between 1992-2002. A total of 76 drillings were made. In total 71 groundwater samples from a total of 55 pipes was analysed in lab. 33 soil samples were analysed.

Pollution situation and ground conditions
The local groundwater direction is in a west direction. South of the location there is a groundwater extraction well, though no longer in use. In the ground there are various pipes present for the thoroughfare of nafta and rainwater. The soil consist mainly of fine to moderate fine and silty sand down to 2 m below soil surface above a massive layer of moderate fine to coarse silty sand down to approximately 20 m where gravel has been encountered. The groundwater table was encountered at approximately 2 m below ground level.

The investigation showed that the site was seriously contaminated (over the intervention value) with mineral oil, volatile aromatic carbohydrates and volatile aliphatic carbohydrates. Maximal concentrations encountered in groundwater (> 9m): benzene 14.000 µg/l, toluene 11.000µg/l, ethylbenzene 2.100µg/l, xylene 5.700µg/l, naphtalene 1,6µg/l, mineral oil (C10-C40) 1.100µg/l, volatile mineral oil (C6-C12) 28.000µg/l.

The contaminated soil was mainly located to the area around the pump plate. The dimension of the contaminated soil was approximately 750 m^3. On top of the groundwater table a layer of very high concentrations of mineral oil and aromatics were encountered. The total volume of contaminated groundwater was defined to 24.000m^3.

Remediation goals

The remediation goal was to reach concentrations in soil and groundwater below the average value[154], within 5 years. For the plume area the goal was to reach a stable end situation within 5 years. Concentrations corresponding to the Average Value are shown in table 13.

Parameter	Goal concentration soil [mg/kg.ds] (based on 2% organic content)	Goal concentration groundwater [µg/l]
Volatile hydrocarbons		
Benzene	<0,1	<15
toluene	<13	<504
ethylbenzene	<5,0	<77
xylene	<2,5	<35
naphtalene	<1,0	<35
C6-C10	<5	<200

Table 13. Goal concentrations at remediation in Oosterhout

Selection of remediation technology
The provincial government demanded a costs-benefit analysis of a multifunctional end situation and functional end situation on the basis of the ROSA document[155]. Following aspects where worked out; remediation cost, duration, risks, after care, continuity of on going activities, risk reduction, improvement of land use possibility, stable end situation, abated amounts and the framework for the remediation goal. A multifunctional approach would involve excavation to a great extent with ground works with ex-site treatment and reconstruction of the pump station. The analysis resulted in difference in cost and duration of factor 4 to a functional approach. A multifunctional approach was not considered realistic and the remediation would be achieved in a functional oriented and cost-effective approach. Potential techniques finally evaluated were

- pump and treat
- 2/3-phase extraction/ soil vapour extraction
- Air stripping (compressed air injection)
- Steam stripping, in situ bio restoration, excavation
- Chemical oxidation.

Criteria for the evaluation were the total price, price to excavate energy costs and the suitability for present contaminants. The evaluation was made by giving the remediation techniques marks from ++ = good performance to -- = bad performance for each criteria. Chemical oxidation with peroxide was chosen together with soil vapour extraction to remediate the source area and compressed air injection for the plume area. The main reason for selected techniques was the short duration of the remediation and the low price. The pipeline company also asked for a total solution for remediating without any excavation. The remediation would be performed as a pilot test to decide whether this solution would be suitable for other contaminated pumping stations.

A case scenario was outlined in case the remediation goals for the various contaminants would not be achieved during the planned remediation. Multiphase vacuum extraction was selected as part of the back up plan.

Results
At this moment the remediation of the plume is still in progress. After two rounds of peroxide injections the effect of the remediation of the source area has decreased. It is probable that all soil will not be remediated and a back up plan has to be started.

Experiences
This was the first remediation with chemical oxidation in the province of Brabant. The authorities

[154] Average Value = 0,5 * (Intervention Value + Target Value)
[155] ROSA = Robust Sanering , document with practical……

where interested in a solution that had the potential to achieve the remediation goal and where very optimistic about the chosen remediation techniques. No special permit was required for the special remediation techniques but to approve the remediation, the authorities demanded a motivation of the selected technique. A description of the impact by the remediation on the surroundings also had to be handed in.

10. Redevelopment of former gas factory terrain in Hilversum

Country
The Netherlands

Contamination
PAH
Mineral oil
BTEX
Cyanides

Technique
Excavation
ISCO by Fenton's reagent

Project status
On-going (2007)

Background
The former gaswork site REGEV Kleine Drift te Hilversum was due to various historical activity heavily contaminated with polycyclic aromatic hydrocarbons (PAH), mineral oil, volatile aromatic hydrocarbons (BTEX) and cyanides. The site is located in an urban area with old factory buildings on it and will be redeveloped to a qualitative high urban residence. Remediation of the site is compelled due to the high concentrations present and change in land use. Responsible for the project is the consortium of the project developer and the building contractor, who share the expenses for the remediation. The project is focusing on remediation of soil, as groundwater will be remediated in a later stage. The site has an area of circa 5 ha and is situated in a residential area. On the location there are several buildings reminding from the gaswork activities.

Site investigation
Approximately 100 soil samples from drilling were analysed in laboratory. No supplementary investigation was needed before the remediation started.

Pollution situation and ground conditions
The soil consists of moderate to fine sand with elements of loam layers down to 4 meters below ground level, continuing in moderate to coarse sand. Groundwater table was encountered at 4 meters below ground level.

Contamination was located to six source areas of different types of polluting sources associated with the historical activity, such as former tank station, gas tanks, tar pits, cleaning house, iron earth regeneration, coke storage. Maximum soil concentrations encountered where for PAH (10): 13 000 mg/kg d.s., Mineral oil (C10-C20) 36 000 mg/kg d.s., BTEX: 11(B), 400 (T), 130(E), 930(X) and cyanide: 620 mg/kg d.s. Down to 7 m below ground level encountered concentrations in the groundwater were for BTEX: 5000-20.000 µg/l, PAH(10) 2000-3000µg/l and mineral oil (C10-C40): 2000-25.000 µg/l. A contamination plume with lower concentrations of benzene and naphthalene was found in the downstream area of the gas factory terrain, with a length of 500 m and a depth of 45 m below ground level. There were still uncertainties of the amount of hot spots and to what extent small pockets of extreme high concentrations of PAH and mineral oil exists.

Remediation goals
The remediation action focuses on cleaning up the source areas. The contamination is remediated in a function-oriented approach, which means that the site must be usable for its future function. Two goals were set for the remediation: 1. For the unsaturated zone there should be no risks posed to human health regarding the function of the site. For the top layer the soil use values for land use class 1 "housing with gardens" be applied. 2. For the saturated zone the remediation of mobile contaminants must be done in a cost-effective way. The remediation must lead to a situation in which no risks are posed to human health and no further spreading to groundwater occurs. The remediation target values were formulated in discussion with the municipality of Hilversum and the province of Noord-Holland. The remediation target values were the same as the soil quality values for recycled soil.

Selection of remediation technology
Excavation was chosen to remediate the top layer, middle layer (down to 3,5 m) and hotspots because it was considered to be fast and reliable. It was also necessary do excavate for the parking basements, why it could be combined with the remediation. Chemical oxidation was chosen because it was considered to be fast and reliable and a suitable technology for reducing cyanides and organic compounds. Before the full-scale remediation started a pilot test was carried out on the site, to confirm previously carried out lab tests. The concentrations after the pilot test were below the remediation target values. As back up in case of unsatisfying progress, an intensifying of the chemical oxidation in the means of more injection of oxidant or more injection rounds will be

realised. Excavation or drilling out of contaminated pockets might be necessary. Permits required for using Fenton's reagent were approval on groundwater infiltration and permit to store peroxide.

Performance
The remediation is carried out in seven parts:

1. Remove al buildings at site.
2. Asbestos inventory
3. Excavations of top layer (<1 m below ground level). 25 % will be transported for treatment off site and 75% will be reused as fill material on site.
4. Excavation of unsaturated zone (down to 0,5 m above groundwater surface)
5. Installation of groundwater wells for surveying of the definitive contaminations in smear zone, hotspots and the rest of the contamination.
6. Pilot tests of chemical oxidation to decide what concentrations of the oxidant should be applied. Start up of groundwater extraction (pump and treat) with infiltration of treated groundwater downstream the groundwater plume. If free phase is encountered in the survey, excavation in the saturated zone will be carried out down to 25 cm under groundwater level. If it's necessary, hot spots will be screened off with iron screens and excavated.
7. Injection of Fenton's reagent.

Results
At this moment, the full scale remediation is just about to be started up.
Experiences
Chemical oxidation has just started.

11. Vegetable oil refinery in Gent

Country
Belgium
(conducted by Witteveen+Bos)

Contamination
Hexane
Benzene

Technique
ISCO by Fenton's reagent
Soil vapor extraction

Project status
2007 completed, evaluation report not finished

Background
At present there is a refinery of vegetable oils operating at the site. Historical refining of car oil on the site had caused a serious contamination of benzene and toluene in both soil and groundwater. To prevent spreading by infiltrating rainwater, a hardened surface layer was constructed over the contaminated area and the contamination was monitored. Due to external development and the profiling as a food manufacturer, the refinery company wanted to remediate the benzene and toluene contamination at the site. The site is located in an industrial area with several buildings. The source area is located under a storage building for solvents. Lorries frequently traffics the ground.

Site investigation
During1995 two site investigations were carried out. In 2003 an actualised site investigation was carried out. After a pilot-test of the remediation technique, an additional investigation was made, with focused on determining the extent of a hexane contamination. A total of 25 groundwater wells were sampled for analyse on BTEX and mineral oil. 10 soil samples from 5 of the drilling points were analysed. Soil and groundwater was controlled before, during and after remediation.

Pollution situation and ground conditions
Top-layer of concrete continuing in a sand layer. At a deep of approximately 3 m there were a peat layer of 0,5-0,7 m thickness continuing in a 20 m thick layer of fine sand. The groundwater table was encountered at a depth of 1,5 meters below surface level.

Vegetable oil was encountered on the groundwater surface. The contamination source was situated to the area used as storage of solvents in the previous activity. The contamination was defined between concrete walls with a total surface area of 200*300 m reaching down to 10 m below soil surface. Therefore the extension of the plume was limited. The soil was mainly contaminated with hexane up to 18000mg/kg d.s. but also aromatics mainly benzene up to 21 mg/kg d.s. groundwater was mainly contaminated with benzene, up to 37000µg/l but also with hexane up to 8000µg/l.

Remediation goals
The goal of the remediation is to reduce the concentrations of benzene and toluene so that irrespective of future situation; there will be no risk for exposure or spreading. Abatement of benzene and toluene with an average reduction of 95% of the start concentration and an average rest

value in the groundwater of 250 µg/l in the source area. Focus will be on remediation of both source and plume. As a result of the remediation the concentrations of xylene, naphthalene, mineral oil and hexane will decrease and the biological activity will increase and contribute to further reduction.

Selection of remediation technology
Remedial solutions evaluated for the site were
- total or partial excavation
- isolation
- in situ biological remediation
- In situ bioventing
- In Situ Chemical Oxidation

Criteria for the evaluation were technical feasibility, environmental benefits, chance of success, costs, impact on the site, impact on surroundings, restrictions on future land use and duration of the remediation. The remediation techniques were given marks from ++ = good performance to -- = bad performance. Chemical oxidation was selected remediation of the benzene and toluene on basis of the evaluation, in particular regarding duration of the remediation, the costs and the feasibility investigation. Another important criterion was that production should be able to continue during remediation. Considering the traffic of loading trucks, excavation would not be a good option. The selection of chemical oxidation and soil vapour extraction was a good option considering that the remediation could continue without disturbing the activity at the factory.

This was the first soil remediation in Belgium performed with in situ chemical oxidation. The authorities approved on the selected technique but required a motivation of the selected technique by a pilot test.

Performance
A pilot test was conducted was conducted in order to decide the proceeding and possible end concentrations in a full-scale remediation and to get insight of the effects on soil temperature, oxygen content in groundwater, pH and alkalinity as a result from the remediation activity. Results from the test confirmed that the selected technique was capable of reducing the concentrations to levels corresponding to minimal future risks. A Soil Vapour Extraction unit was installed in order to capture released oxygen, carbon dioxide (CO_2) and possible volatile gases in an active carbon filter that were combusted.

Results
Evaluation report not completed.

Experiences
The peat layer at 3 meters depth was a source of uncertainty. Peat can adsorb benzene and result in a sponge effect with settlements in the ground. 11 months after the pilot test, the concentrations of benzene raised to very high levels. This may be an effect of the present peat layer or caused by monitoring filters that had not been changed. As a result the contaminants will migrate the same way and lead to increased concentrations in the monitoring points.

SKB (Centre for Soil Quality Management and Knowledge Transfer)
SKB is a network organisation with the aim to contribute to a faster and more cost effective cleanup of contaminated sites in the Netherlands. The network is a combination of both public and private interests and work with development of knowledge and with facilitating knowledge transfer within the field of contaminated soil. The focus is on problem owners who look for cost-effective solutions to their contaminated land. The objective is to contribute to a higher knowledge of the technology and a wider acceptance. SKB started in 1999 and have a guaranteed financing of two million euro each year from the Ministry of VROM until 2010. Totally the SKB have a budget of 3,5 million euros until 2010. The network has a wide representation from several departments, problem owners, authorities, contractors, consultancies, universities, financiers, estate developers etc. All activities are financed on a project basis where SKB represent approximately 70% of the costs and a mix of parties with interests for the remaining 30%. The projects are grouped into four categories: investigation, research, knowledge projects and demonstration projects.

More information is available at: www.skbodem.nl

SIKB (Foundation Infrastructure for Quality Assurance of Soil Management)
SIKB provides instruments for simpler and better soil management.
SIKB is a network, encompassing both the private and the public sector, set up to continuously and structurally enhance the standards of activities relating to soil management in The Netherlands. This includes decision-making, rendering of services, as well as soil remediation and soil handling.

The mission of SIKB breaks up into five goals:
1. Further harmonisation of applied procedures and technology
2. Application of improved technology and procedures
3. Economic and cost aware execution of work
4. Well defined definition of quality and making quality assurance identifiable by certification
5. Getting and keeping support from all parties concerned

More information is available at: www.sikb.nl

TCB (The Technical Committee on Soil Protection)
The TCB is an independent committee based on the soil protection act. The committee makes recommendations on the technical and scientific aspects of soil protection. The TCB is generally consulted by the Ministry of Housing, Spatial Planning and Environment and the Ministry of Agriculture, Nature management and Fisheries. Besides its advisory capacity, the TCB has an informative function. Not only civil servants and politicians but also those active in education and the commercial sector increasingly consider the TCB as part of their information network. The TCB also functions as a platform for discussion. The TCB consists of 11 leading experts well grounded in the areas involved in the technical and scientific aspects of soil protection such as hydrology, cultivation techniques, soil science, toxicology and ecology.

More information is available at: www.tcbodem.nl

SenterNovem/Bodem+

The organisation was established in 2005. It is positioned in between the Ministry of Spatial Planning and Environment (VROM) and the local authorities such as municipalities, provinces and water ships.
The mission of Bodem+ is as formulated: ”*Putting policies and legislation into practice and visa versa."*

Tasks performed are mainly derived from current legislation. Further tasks include advising and some reminding tasks:

- Assessment of site remediation programmes and soil treatability;
- Mapping of the environmental quality of the Dutch soil;
- Prioritising of public funding for site remediation based on a risk assessment model.
- Strategic and hands-on advice to local authorities in all matters involved with soil and sediment issues (e.g. remediation, reuse, land filling, treatment);
- Based on a thorough knowledge of current practises inputs are given for new policy development, to ensure practical operability.
- Knowledge development in the areas of risk assessment (leaching and eco toxicological), site and soil sampling procedures, in and ex situ treatment technologies;
- Knowledge transfer.

More information is available at: www.senternovem.nl/bodemplus/index.asp